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MEASURING INSTRUMENTS

JOHN C. CONNAN

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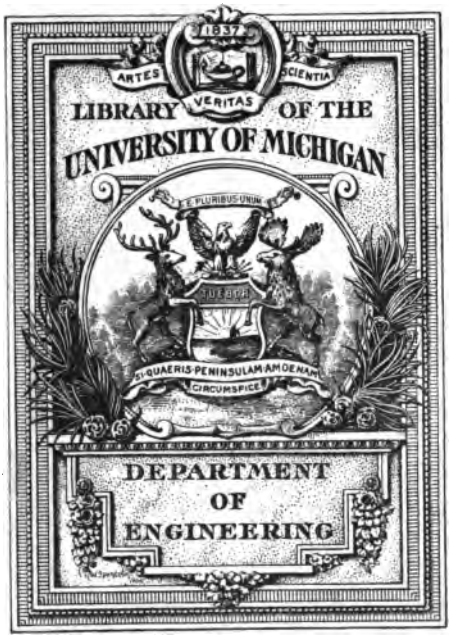
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SWITCHBOARD MEASURING INSTRUMENTS

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SWITCHBOARD MEASURING INSTRUMENTS

FOR

Continuous and Polyphase Systems

BY

JOHN C. CONNAN

London
E. & F. N. SPON, LIMITED, 57 HAYMARKET
New York
SPON & CHAMBERLAIN, 123 LIBERTY STREET
1908

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PREFACE.

THE object of the following pages is to supply, what has long been felt by those most interested in the subject of electrical instruments, the need of a short volume dealing with the design and construction of this type of apparatus. Their substance, as may be seen from the Appendix, has been collected from numerous reviews, magazines, and papers read before various learned societies; and is arranged in a form which, it is hoped, may prove to be concise, convenient, and easily intelligible. In the descriptions of the various instruments, as much of the details of construction as have been thought necessary to a correct understanding of the subject, have been given. But exact information of any particular make, has, as far as possible, been avoided; such figures as there are, may be taken as representing average practice.

My thanks are due to Prof. S. P. THOMPSON, D.Sc. F.R.S., for his kindly encouragement and help; to Dr. DRYSDALE, D.Sc., for much information and assistance; and to Mr. HOWGRAVE-GRAHAM for suggested alterations and improvements and for kindly looking through the sheets.

I have further to thank the numerous manufacturers whose names appear in the text or on the blocks, for their kindness in supplying me with particular information on, and illustrations of, the various instruments of their manufacture.

LONDON, *March*, 1908.

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SWITCHBOARD MEASURING INSTRUMENTS

FOR

CONTINUOUS AND POLYPHASE SYSTEMS.

CHAPTER I.

INTRODUCTION.

THE discovery by Faraday, in 1831, that a current was induced in a wire, when it was moved across a magnetic field, made the commercial use of electricity a possibility, since it showed how mechanical energy could be directly converted into electrical energy. It was not, however, till about 1867, when the first attempts at dynamo building were made, that this great discovery was put to any practical purpose. As soon as the first dynamo was built and the way for great commercial development opened up, electrical measuring instruments became a necessity in order that what was going on in the circuit might be known. Instruments were in use before the dynamo was thought of, but they were not the class of instrument that could be handed to the consumer of electricity for every day use. Consequently, with the birth of the dynamo came the birth of a new industry, that of electrical measuring instruments which were accurate but not delicate in construction.

A measuring instrument may be defined as an apparatus which gives a means of obtaining the relation between the quantity which we desire to measure and another fixed quantity of the same kind, called a "unit." Before proceeding

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further, it will be well to state the practical units which are in use in the different instruments which come under consideration. These practical units are in the first place derived from absolute units, definitions of which may be found in almost any text book dealing with electrical engineering. Confining our attention therefore entirely to the practical units, they may be defined as follows :—

Current.—When an unvarying current flows through a solution of silver nitrate in water and deposits silver at the rate of 0·001118 gramme per second, then this strength of current is called an "ampere."

An alternating current of one ampere is that current which when allowed to flow in a conductor, maintained at a constant temperature, produces heat at the same rate as would be produced by a continuous current of one ampere under the same conditions. This is known as the "root mean square" or "virtual" value.

Voltage.—The unit of voltage is defined to be that electromotive force which when applied to a resistance of one ohm will cause a current of one ampere to flow in it. This is known as the "volt."

An alternating E.M.F. of 1 volt or a virtual volt is that electromotive force which when applied to a conductor at a constant temperature, causes a current to flow of such a magnitude that the rate at which heat is produced is equal to the rate at which it would be produced by a continuous E.M.F. of one volt under similar conditions.

Resistance.—The unit of resistance is taken as the resistance of a column of mercury 106·3 cm. high and 14·4521 grammes in mass at 0° C. This is known as the "ohm."

Power.—Electrical power is measured in terms of a unit called the "watt," which is defined as the electrical power expended in a circuit when a current of one ampere flows under the pressure of one volt.

Horse-Power.—The equivalent in electrical energy of a mechanical horse-power is taken as 746 watts.

There are certain other properties and relations of an electrical circuit which it is indispensable for an engineer to

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know. Below will be found definitions of such as concern this subject.

Phase-Difference.—The common practice of representing alternating quantities by vectors, allows the phase-difference between two quantities to be defined as the angle between the vectors representing the two quantities.

Lag and Lead.—One electrical quantity is said to lag with respect to another, when the vector representing the former passes through the zero position later than the vector of the latter; it is said to lead, when it passes through the zero position before the latter.

Power Factor.—The name given to the cosine of the angle of lag or lead is the "power factor," and it is also the ratio of the true watts to the apparent watts.

Wave Form.—The variations of an alternating quantity with respect to time may be graphically represented, which representation is called the "wave form."

Frequency.—The number of complete cycles of an alternating quantity in one second is called the "frequency."

Having stated the units by which the various properties of the circuit may be measured, it is now necessary to enunciate the principles on which commercial instruments are generally constructed before proceeding to describe the instruments themselves.

These principles are six in number and are all derived from experimentally established facts.

1. Magneto-Dynamic Principle.

This is based on the fact discovered by Oersted in 1820, that a force is exerted between a wire carrying a current and a permanent magnetic field. The first instruments made on this principle were due to Lord Kelvin and M. D'Arsonval.

2. Electrodynamic Principle.

This principle is based on the fact discovered by Ampère in 1821, that a force is exerted between two conductors carrying currents.

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Instead of, as in the previous case, a field due to a permanent there is substituted one due to an electromagnet.

3. Electromagnetic Principle.

This principle is based on the law that in every electromagnetic system forces act between its parts in such a way as tends to reduce the reluctance of the system to a minimum.

4. Electrothermic Principle.

The well-known fact that heat is produced in a conductor, when a current flows in it, is the basis on which this principle is founded.

5. Electrostatic Principle.

When two charges of electricity are brought near to one another, a force is exerted between them, and upon this fact is based the principle on which electrostatic instruments are constructed.

6. Principle of Resonance.

If a series of small impulses be applied to a vibratory medium whose period of natural vibration is the same as the period of the impulse, then they will produce a greatly magnified corresponding series in the medium.

What properties and relations of a circuit are most frequently required to be measured, and on which of the foregoing principles can these measurements be most efficiently made, are the questions which have next to be settled. The answers to these questions have been set forth in Table I. below, where however, a further sub-division has been made to indicate the difference between instruments intended for alternating and continuous current systems.

To present this matter from another point of view, a further Table (II.) has been given below, showing the different properties and relations which may be measured by any one principle as defined above.

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TABLE I.

	Property or Relation to be Measured.	Principle on which is based the instrument intended for	
		Continuous Current Circuits.	Alternate Current Circuits.
1	Current	*Principle.* 1. Magneto-dynamic 2. Electro-dynamic 3. Electro-magnetic 4. Electro-thermic	*Principle.* 1. Electro-dynamic 2. Electro-magnetic 3. Electro-thermic
2	Voltage	1. Magneto-dynamic 2. Electro-dynamic 3. Electro-magnetic 4. Electro-thermic 5. Electro-static	1. Electro-dynamic 2. Electro-magnetic 3. Electro-thermic 4. Electro-static
3	Resistance. . . .	1. Magneto-dynamic 2. Electro-dynamic 3. Electro-magnetic 4. Electro-static	1. Electro-dynamic 2. Electro-magnetic 3. Electro-static
4	Power	1. Electro-dynamic	1. Electro-dynamic
5	Frequency . . .	..	1. Electro-dynamic 2. Electro-magnetic 3. Resonance
6	Power factor . .	..	1. Electro-dynamic
7	Wattless component of the current	..	1. Electro-dynamic

Before giving a detailed description of the various instruments working on these principles, it is important to know the object at which the manufacturer aims. It will be generally allowed that his chief aim is accuracy with low power-consumption and cheapness. The question as to what is a suitable or sufficient accuracy is one which has led to considerable debate. A very accurate instrument say $\frac{1}{5}$ per cent. will cost considerably more than one whose accuracy is 1 per cent.; but where does the advantage of the greater accuracy lie, since a switchboard attendant cannot be relied upon to read within 2 per cent. under ordinary working conditions? Is it not better to be able to rely on the readings of an instrument, whose cost is moderate, itself accurate to within 1 per cent. when on the switchboard and in work, than to have a very accurate instrument whose cost was considerable, since in both cases the total error in reading must be between 2 and 3 per cent.?

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TABLE II.

Type.	Principle on which Instrument is based.	System.	——	Name of Instrument.
A	Magneto-dynamic	Moving coil . . .	*a*	ammeter
			b	voltmeter
			c	leakage indicator
B_1	Electro-dynamic	Moving coil (1) air core	*a*	ammeter
		Moving coil (2) iron core		
			b	voltmeter
			c	wattmeter
			d	phasemeter
			e	idle current wattmeter
B_2	,, ,,	Induction (1) shifting field	*a*	ammeter
			b	voltmeter
			c	wattmeter
			d	idle current wattmeter
			e	frequency meter
			f	leakage indicator
		Induction (2) revolving field	*a*	ammeter
			b	voltmeter
			c	wattmeter
C	Electro-magnetic	Moving iron . . .	*a*	ammeter
			b	voltmeter
			c	horse power meter
			d	ohmmeter
			e	leakage indicator
			f	frequency meter
D	Electro-thermic	Hot wire	*a*	ammeter
			b	voltmeter
E	Electro-static	Moving vane . . .	*a*	voltmeter
			b	leakage indicator
F	Resonance	Vibrating reed . .	*a*	frequency meter

Further, if, as is sometimes necessary, the customer has to choose from several instruments possessing practically the same accuracy, etc. but differing in price, he will probably decide on the cheapest losing sight of the fact that he will have a continuous charge for power-consumption which is generally greater in the cheaper instruments.

Below will be found a table giving the power-consumption

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of most of the types of instrument described in the chapters which follow.

TABLE III.

Type.	Instrument.	Range		Current taken (amps.).	Voltage Drop (volts).	Power Consumption (watts).
		From	To			
A	Ammeter	0	500	..	0·08	40
	Voltmeter	0	200	0·01	..	2
		100	200	0·02	..	4
B_1	Ammeter	0	18	..	0·9	16
		0	100	..	0·5	50
	Voltmeter	0	200	0·05	..	10
	Wattmeter	0	100 V / 100 A	0·32	0·93	42
	Phasemeter	P.F. 1·0 – 0 (100 volts)		0·07	0·05	10
	,, (Westinghouse)	P.F. 1·0 – 0 (100 volts)		0·07	0·05	7–10
B_2	Ammeter (revolving field)	0	5	..	1·8	9·0
		1	120	..	0·3	25·0*
	Voltmeter (revolving field)	0	110	0·064	..	7·0
	Wattmeter (revolving field)	0	110 V / 5 A	0·023	0·13	3·2
	Wattmeter (shifting field)	0	100 V / 100 A	0·05	0·015	6·5
	Frequency meter	50~	(100 volts)	0·15–0·20	..	15–20
C	Ammeter	0	5	..	0·2	1·0
		0	10	..	0·3	3·0
		0	100	..	0·03	3·0
		0	500	..	0·01	5·0
	Voltmeter	0	10	0·2	..	2·0
		0	100	0·06	..	6·0
		0	200	0·05	..	10·0
		0	500	0·04	..	20·0
		60	120	0·05	..	6·0
D	Ammeter	0	500	..	0·2	100·0
	Voltmeter	0	200	0·17	..	34·0
		20	120	0·21	..	25·0
E	Voltmeter	any range		..	..	0
F	Frequency meter	50~ (100 V)		0·05–0·1	..	5–10

* Worked from current transformer, secondary current = 5 amps.

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CHAPTER II.

GENERAL REMARKS.

THERE are two main classes into which instruments may be divided—

1. Alternating current instruments.
2. Continuous „ „

In two cases, types D and E, the instruments may be used on either A.C. or C.C. circuits without altering the accuracy, and type C could be used, if very accurate readings were not of importance. There are a few constructional details which have to be observed in making A.C. instruments which do not occur in C.C. work, made necessary by the induced eddy currents in masses of metal inside the instrument. They are, that all metal bobbins should be split, and that small metal parts such as spindles, bridges, etc. should be made of a high resistance material, such as German silver, which is practically free from eddy currents.

Both of these classes of instruments can be made as either

1. Indicating instruments ; or
2. Recording „

As the name implies, an indicating instrument simply shows what the value of the current, voltage, etc. may be at any particular time, and does not make a permanent record of that value, this being the function of the recording instrument. The movement used in the latter is practically identical with that used in the former, the only difference between them being that owing to the friction introduced by the pen a larger power consumption is required, and consequently the necessary means to supply this want have to be provided. The recording appa-

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ratus, Fig. 1, which shows the construction of an Elliott recorder consists, of a drum driven by clockwork to which is attached a chart upon which the pen of the movement records. The pen, Fig. 2, is generally of the form of a small reservoir for ink with a very fine capillary tube through which the ink

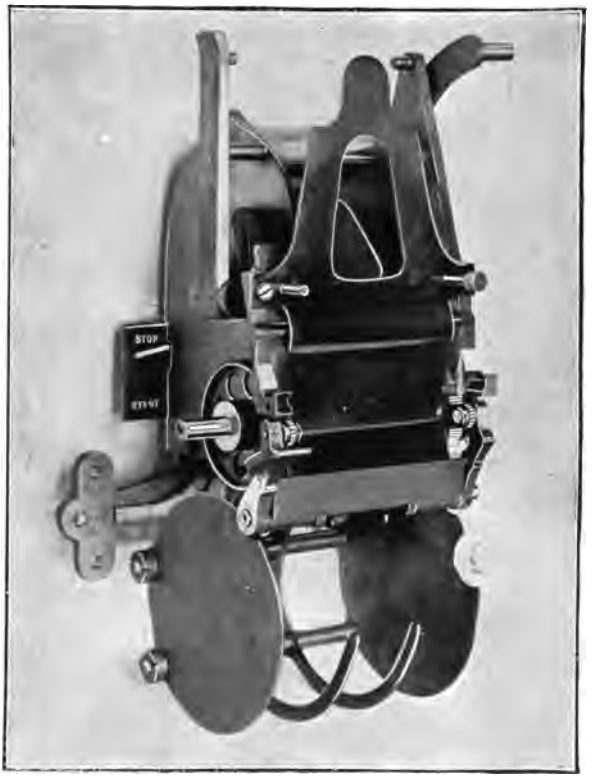

FIG. 1.

flows on to the chart; this pen is attached to the end of the pointer which in this case hangs downward.

The troubles caused by the ink have led Messrs. Everett, Edgcumbe to introduce a new arrangement in which ink is dispensed with, see Fig. 3. By means of a "synchronome" clock, see Fig. 4, they give a hard steel style a succession of light blows, the common rate being one every five seconds.

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Between the steel style and the chart is stretched a carbon ribbon which records the blows as a dot, and at the speed mentioned these dots are so close together that the record appears practically continuous.

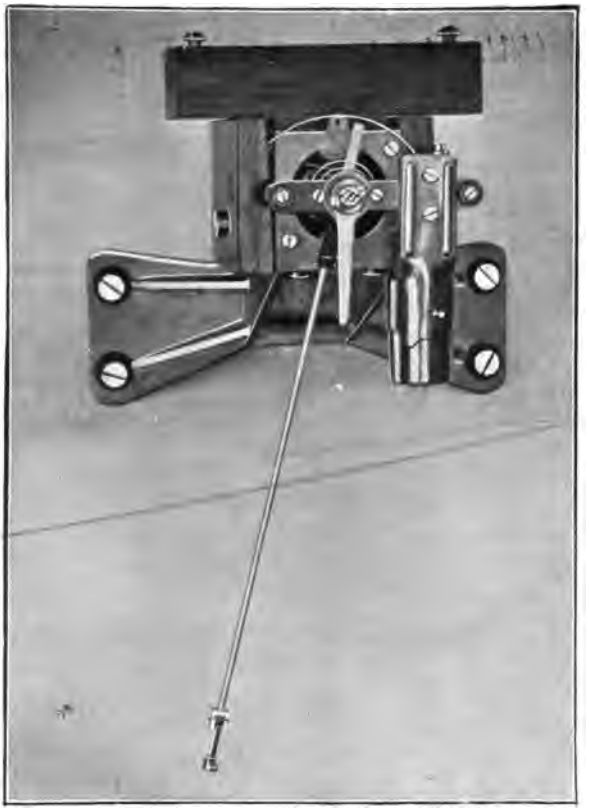

FIG. 2.

The usual speed for recording clocks is 1 inch per hour, but this speed can be varied within wide limits to suit the purpose for which the instrument is intended.

The movement for the switchboard pattern is fixed into a case, such as shown in Fig. 3, but these instruments may be made portable by fixing them into a much lighter case, as shown in Fig. 5.

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Pot or Case.—There are three metals which are commonly employed for the construction of this part, they are iron, brass, and aluminium, ranged in the order of their utility. Iron, the commonest of all, is an excellent material to use for this purpose since it possesses great magnetic shielding power, takes a

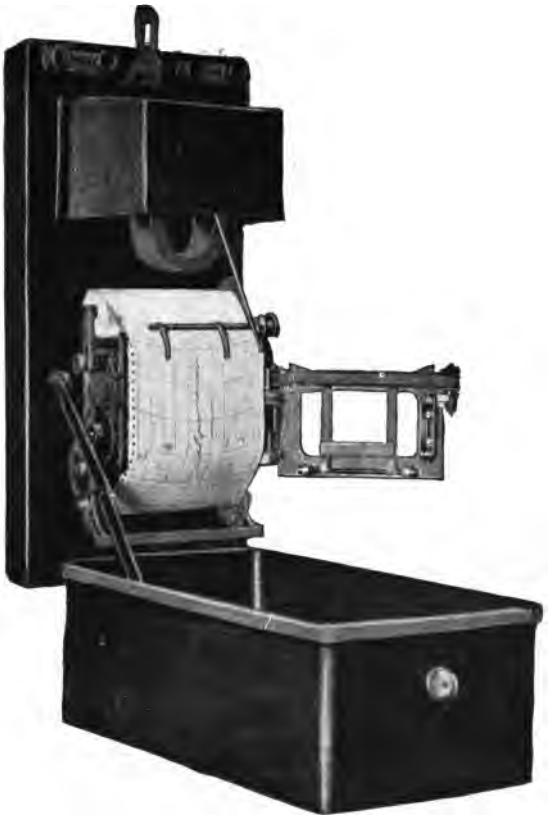

FIG. 3.—RECORDER WITH CASE OPEN, AND TAPPER FRAME TURNED BACK.

good finish, see Fig. 6, and is strong and cheap. Brass is used only in such instruments as are unlikely to be brought under the influence of strong magnetic fields, and gives a strong pot capable of taking a fine finish, see Fig. 7. Aluminium is not largely used, but is of advantage where lightness is important

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which is discounted by its lack of strength although it takes a smart finish, Fig. 8.

The pots are generally cast to the required shape but in the case of the first two they are also often found made up from thin sheets. For alternating current instruments where

FIG. 4.—ELECTRIC CLOCK.

eddy currents are likely to be generated in the metal case some makers prefer to construct the pot of a non-metallic substance, such as ebonite, stabilit, or ambroin. These pots of course cost more than the ordinary cast pot, but they will take a very nice finish which is preferred by some to the ordinary metal finish,

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FIG. 5.

FIG. 6.

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see Fig. 9. This non-metallic case was largely used for wattmeters, and phasemeters, owing to the serious error which

FIG. 7.

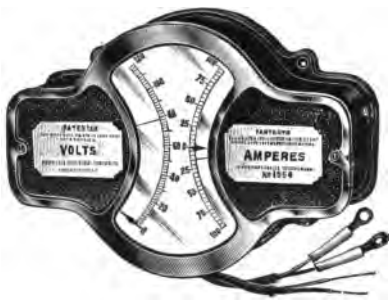

FIG. 8.

eddy currents introduce into these instruments at low power factors, but by careful design these instruments can now be

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had in cast-iron pots, the error introduced being small, as can be seen from curve, Fig. 10, for a wattmeter range 0–50 k.w.

The shapes which the pot takes are very numerous, depending to some extent on the work which the instrument is required for. The form most generally met with is the round pot, see Fig. 6, which is suitable for a great variety of conditions ; but is not easily converted into an illuminated dial instrument, owing to the large amount of space which would be wasted. The edgewise form was an endeavour to meet the

FIG. 9.

demand for an instrument which took up little room on the switchboard and whose scale could readily be seen. This form may take three shapes ; (1) the overtype, where the scale is placed underneath, the instrument being in a position above the line of the attendant's eye ; (2) the horizontal type, where the scale is horizontal ; (3) the under type, where the scale is above, the instrument itself being under the attendant's eye. See Figs. 11, 12 and 13. Fig. 12 is the photo of a vertical scale instrument, which may be used in a horizontal plane, if the

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figures are placed accordingly. The body of these instruments may be placed in a hole cut in the switchboard, when only a small part of the instrument—that containing the scale arrangement—will project outwards ; a point of great importance

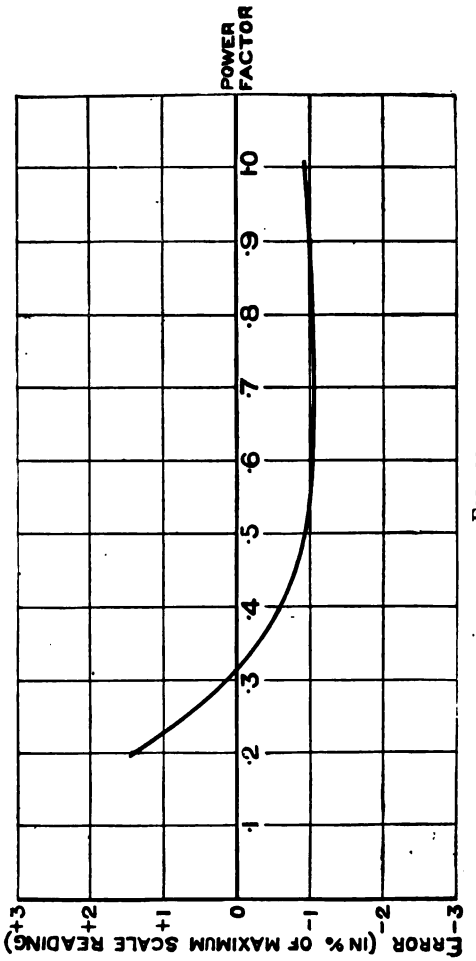

FIG. 10.

where the board is restricted in space. There is a very great disadvantage attendant on the use of this form, viz. the large error, due to parallax, which may be introduced when taking a reading. Since the reading has to be made on a scale along

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the edge of a circle, it follows that, if of comparatively small radius such as has to be used in instruments, there will be a place where the pointer and scale will appear to the attendant to approach the parallel. Here the error due to parallax will

FIG. 13.

FIG. 12.

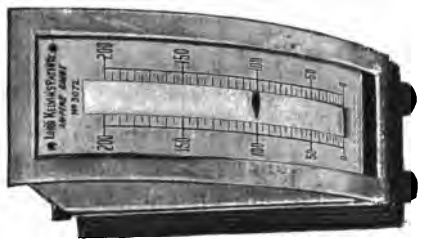

FIG. 11.

be greatest, but will gradually fall off as the pointer comes into the shortest line between the scale and the man's eye.

Where the instruments are placed at some distance from the attendant, or in a dark situation, it becomes necessary to

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illuminate the dial. This may be done by throwing a light on to the scale from the front, or through the scale from behind ; the latter being the more satisfactory. This necessity for illumination in round instruments, which we have seen to be difficult, led to the introduction of the sector or thistle shape, see Figs. 14, 15, 16.

FIG. 14.

In cases where a simultaneous reading of amperes and volts is an advantage, the two instruments may be arranged in one pot so as to indicate on one scale, in such a manner that both pointers may be easily read at the same time, and readings taken very quickly, see Fig. 8.

In the case of all pots the lids must be hermetically sealed to prevent moisture from getting to the movement.

In the "Portable" type, see Figs. 17 and 18, the case (lined with sheet iron to shield the movement) is usually made

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FIG. 15.

FIG. 16.

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of a hard wood, as teak, walnut, or mahogany, which will stand rough usage and take a good finish.

Opening.—The opening provided in switchboard instruments for reading the scale are very diverse in shape, as can be seen from Figs. 6, 8, 13 and 19; but as long as the scale can be easily seen and the appearance of the instrument is pleasing, it does not matter at all what shape is used. The opening is fitted with glass and sealed in a similar fashion to the lids mentioned above.

FIG. 17.—PORTABLE VOLTMETER.

Scale.—The scale is a very important part of the instrument, and is one where errors may quite easily creep in, since small errors may be introduced both by the calibrator and printer. Taking an average case of preparing and fixing the scale for a moving iron voltmeter, an error of $\pm 0{\cdot}7$ per cent. is sometimes found as the result of these operations. The earliest scales were engraved on metal. These are now practically obsolete, since they were expensive to produce and

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generally inaccurate. Printing on enamel has been tried, but was given up in preference for printing on paper or thin cardboard. The latter is much cheaper and on it the scales can be produced with greater accuracy than on other mediums. The cardboard is usually of a dull surface to prevent the reflection of light from interfering with ease in reading, and is cemented to a metal plate, generally of zinc, to keep it stiff. In illuminated dial instruments the scale is made of opal glass, the markings being etched in by hydrofluoric acid. The

FIG. 18.

markings of the scales for switchboard instruments should be fairly thick so as to be distinctly seen at some distance away. They should not be too numerous, especially in that part of unequally divided scales where the marks are close together, somewhere about 50 in a 5½-inch scale. About the best possible length of scale will be one which subtends an angle of not more than 75° at the centre of the movement. In scales having an angle of from 100° to 120°, parallax causes an error when a reading is made near the top or bottom point ;

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and in scales which are nearly a complete circle there is also an awkwardness in placing the figures, so that they are difficult to read, see Fig. 19.

FIG. 19.

FIG. 20.

Pointers.—The pointers must be bold, but should have their tip about the same width as the markings of the scale. The "spearhead" pointer, shown in Fig. 20, is one of the best.

Controlling Force.—In every electrical measuring instrument there are two positions of rest for the movement; one when no current flows, the other when the axis of the moving system lies in the line

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of the deflecting force. This last position is independent of the magnitude of the deflecting force, being solely governed by friction ; consequently, it is necessary to introduce a controlling force to make the deflection proportional to the magnitude of the deflecting force. The controlling forces employed are :—

1. The pull of a helical spring, as in Swinburne instruments.
2. The twist of one end relatively to the other of a helical spring, as in the Ayrton and Perry instruments.
3. The torque of a spiral spring.
4. The force of gravity.

Numbers 3 and 4 are now practically the only ones used in commercial instruments. The spiral spring makes an excellent control ; for, if the spring has been well aged, it remains almost constant, and no great care need be exercised in fixing the instrument perpendicularly. Sometimes instead of using one spring only, two are employed set in opposition to one another so as to minimise errors of elongation due to variations in the temperature.

On the other hand, the gravity control is much cheaper ; and, as it is absolutely constant within the limits of the force of gravity, it is equally good except that the instrument must be fixed level, otherwise a zero error will occur. But this error, where it does occur, can be easily estimated and allowed for.

Damping Devices.—In ordinary practice the load on the mains is never steady for any length of time. It is easily seen, therefore, that if the instruments used are to follow accurately the variations in the load they must be very dead-beat. Without some form of control to damp the oscillations of the movement, accurate readings would be impossible, since the large moment of inertia and the small amount of friction at the pivots would tend to make the pointer take a large swing for a small increase or decrease in the deflecting force, that is, when a small increase or decrease in the load occurs.

The common devices used to make the motion dead-beat may be divided as follows :—

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1. Magnetic — Fig. 7.
2. Fluid — *a.* Air, Fig. 98. *b.* Liquid, Fig. 21

All three methods are in general practice, but perhaps 1 and 2*a* are more frequently used than 2*b*.

1. Magnetic damping depends on the induction of eddy currents in metal parts when they are moved so as to cut magnetic lines. In those instruments where metal frames are used, the necessary damping control is supplied by the eddy currents induced in them, but where no metal is used in the construction of the frames, a disc of copper or aluminium is generally fixed to the spindle, so that its rim revolves between

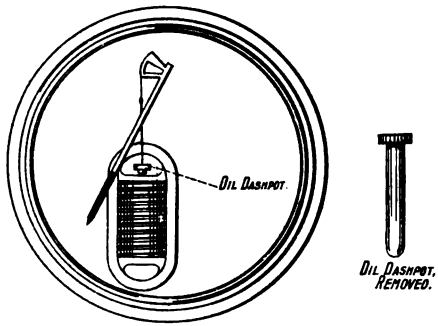

FIG. 21.

the poles of a small permanent magnet which has been well aged. This type of damping device is impracticable for alternating current instruments, unless the coils are shielded so as to protect the magnet against the weakening action of alternating fields.

2*a*. The use of the resistance offered to a small light vane when moved in air is the most satisfactory method of damping the motion, because it is absolutely constant, and the necessary apparatus is easily made. The vane is usually attached to an arm fixed to the spindle, both vane and arm being as light as possible in order not to appreciably increase the moment of inertia of the movement. The vane usually moves in a box or a cylinder; the clearance left between it and the sides of the enclosing vessel is very small, so that the air resistance may be as large as possible.

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2*b*. Liquid damping is the oldest type of damping employed for commercial instruments. It cannot, however, be used at all in portable instruments, and is not very satisfactory when put into those intended for switchboard work. The principle of this device is the same as that used in the previous one, but instead of the light vane moving in air, it moves in a vessel containing a viscous liquid as oil or glycerine. Care should be taken that no part of the vane comes above the surface of the liquid, otherwise some of the liquid will adhere, and "creeping" in the reading will result.

Shunts.—In order that the current flowing in an ammeter moving coil may be proportional to the current in the main

FIG. 22.

circuit, a section, of low resistance and negligible temperature coefficient, has to be inserted in one of the mains. To the ends of this section the terminals of the instrument are connected. This section is usually known as the "shunt," and consists of two large terminal blocks of copper or brass between which are sweated, brazed or cast, the low resistance material to be used, see Fig. 22. This material, usually eureka, manganin or constantan, takes the form of either wire, rod or sheet, depending on the range of the shunt, and is arranged so as to present as large a radiating surface as possible to the air. The voltage drop across this shunt varies from 0·06 to 0·1 volt in type A instruments, and is somewhat higher than this for instruments of types C and D.

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External Resistances.—These are used with such instruments as require the current flowing in their coils to be proportional to the voltage. They generally consist of the same material as the shunt, wound in the form of a coil whose resistance remains practically constant at all ordinary working temperatures. Sometimes they are placed inside the instrument; but this is only done for low ranges, since the heat radiated by the coil may produce alterations in the resistance of the moving coil, and thus introduce errors. More generally they are met with in metal boxes with perforated sides, so as to dissipate heat as rapidly as possible.

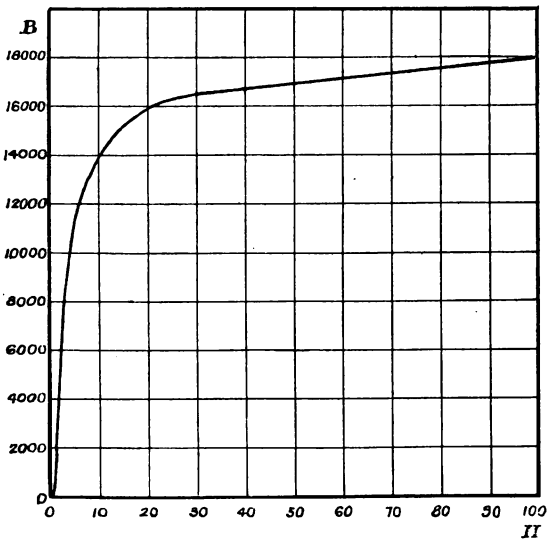

FIG. 23.

Transformers.—Faraday's well-known experiment, of winding two coils of wire on a ring of iron, through one of which he sent a current, and from the variations of this current obtained from the second coil another current, may be regarded as the foundation of modern transformers. In these the iron ring is replaced by a laminated core, usually of rectangular shape, possessing a closed magnetic circuit. The laminations are of the best soft iron obtainable (for B and H curve, see Fig. 23),

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and are between 12 and 18 mils thick, with some form of insulation between them, generally thin tissue paper or shellac varnish. On this core are wound the primary and secondary coils, the size of wire and the number of turns required for each depending on the work which the transformer has to do.

The disposition of the copper and iron provides a convenient but somewhat indefinite means of classifying transformers with regard to their construction. When the copper is entirely

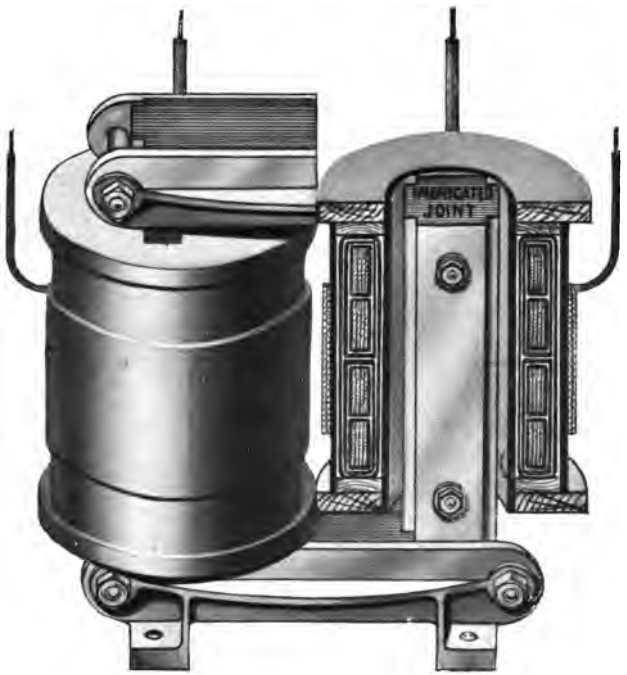

FIG. 24.

surrounded by iron, it is called a "shell" or "mantle" type transformer, whereas if the copper is not completely surrounded by iron, the transformer is said to belong to the "core" type. With regard to their work there are also two classes into which transformers may be divided, viz.—

1. Voltage, pressure, or potential transformers. (Figs. 24 and 25.)

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2. Current and bus-bar transformers. (Figs. 26, 27 and 28.)

Voltage and current transformers may be made in either shell or core type, but when intended for instrument work are, as a rule, made in the latter.

FIG. 25.

Voltage transformers are those in which a current at a high potential is stepped down to a current at a much lower potential. The insulation employed to separate the primary and secondary coils from one another and the core from the coil wound next to it, must necessarily have a high dielectric strength. For this purpose, tubes made of mica and good adhesive varnish are generally used. The primary coil, that

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is, the coil supplied with current at high potential, is usually divided into a number of sections each separately insulated. These undergo several processes, in each of which they are dried and impregnated with a good insulating varnish; they are then grouped together and placed on the core thus forming the primary winding. The secondary winding will require

FIG. 26.—CURRENT TRANSFORMER, CORE AND COILS ONLY, SHOWN WITHOUT THE INSULATION.

only a small number of turns of wire, since the current taken by a voltmeter is small. Where a number of instruments are to be worked from one transformer, it is necessary to have a sufficient number of turns to supply the current required. It is further a great advantage to have the drop on the secondary winding small, not more than 1 per cent., for then it is permissible to assume that

$$E_2 = E_1 \frac{S_2}{S_1}$$

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where E_2 = secondary voltage
E_1 = primary voltage
S_2 = no. of secondary turns
S_1 = no. of primary turns

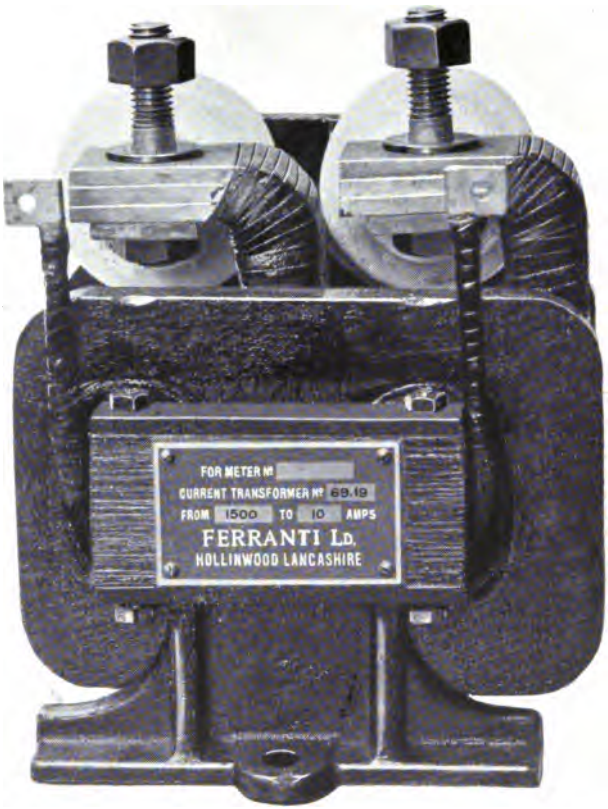

FIG. 27.

since in this case the instrument may be calibrated directly on the lower voltage instead of being calibrated in conjunction with the transformer.

In Figs. 29 and 30 are embodied the results of a series of

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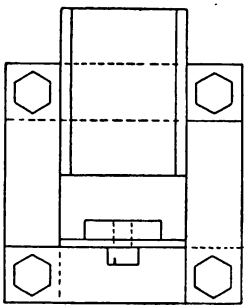
tests on a voltage transformer made by Dr. Drysdale, for fuller particulars of which reference should be made to *The Electrician*, vol. lviii. p. 160. Fig. 29 shows the variation in the ratio of transformation, and Fig. 30 the alteration in the phase-displacement between the primary and secondary voltages, when different loads are applied to the secondary. The curves were obtained when the load was respectively (1) zero, the secondary being on open circuit; (2) a non-inductive load of 2400 ohms, and (3) an inductive load of 900 ohms impedance.



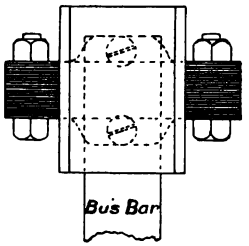


FIG. 28.

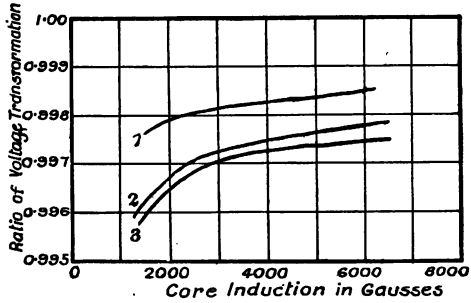


FIG. 29.

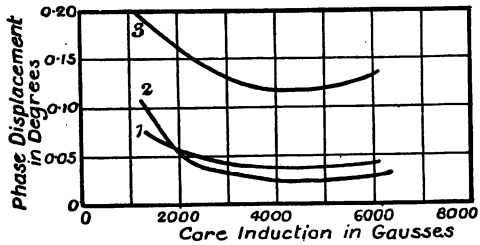


FIG. 30.

The principal points to be noted in the design of voltage transformers are that :—

1. The resistances of the coils are made as small as possible.

2. The primary and secondary coils be wound as close together as the construction will permit, so as to make magnetic leakage very small.

Current transformers are similar to the former, but must

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be provided with a primary winding capable of carrying the current to be transformed. If the voltage of the system on which they are to be used is high, then as much care must be given to the insulation as was exercised in the previous case.

As a rule the primary winding is wound on the outside of the secondary, so as to provide a large radiation surface. But in the case of bus-bar transformers, where the bus-bar carrying the current to be measured is to be used for the primary, the secondary is wound on one limb of the core, and the whole apparatus fixed to the bus-bar in such a manner that the maximum number of lines thread through the coil. (See Fig. 28.)

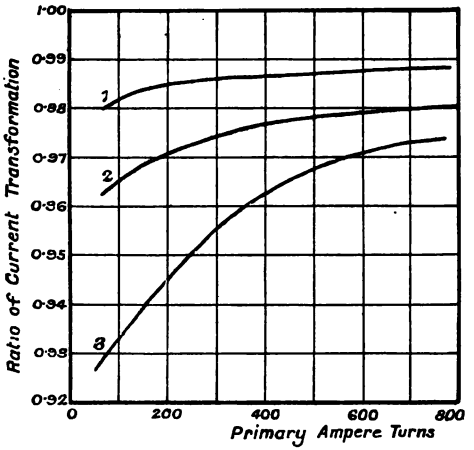

FIG. 31.

In circuits carrying heavy currents from 800 amperes and upwards, a transformer is indispensable, since it allows a simpler and cheaper instrument to be used, whilst it gives an accuracy quite as good as if a heavy current instrument were used. The secondary is wound of such a wire as will give from 5–10 amperes at 100–200 volts.

In the case of current transformers it has been shown that the instrument to be used in order to obtain approximate constancy of ratio over a wide range of load is one possessing a low resistance and reactance. It is not correct, therefore, to assume that the readings given by an instrument are accurate,

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unless it has been calibrated in conjunction with the transformer in whose circuit it is to be connected. Fig. 31 gives the results of tests made on a current transformer (see paper mentioned above) to show how the ratio of transformation varies with the load. Curve No. 1 was obtained when the secondary was short-circuited, curve No. 2 when there was a non-inductive secondary load of 5·9 ohms, and curve No. 3 when a lagging inductive load was used, the impedance of which was 5·7 ohms, and cos $\phi = 0{\cdot}222$. Fig. 32 gives the corresponding phase-displacements between primary and secondary currents when the loads were varied as before.

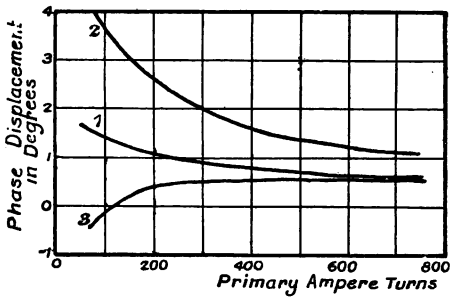

FIG. 32.

These transformers ought to have :—

1. A small magnetising current with small magnetic reluctance and low induction density.

2. Small impedance in the secondary circuit.

Materials.—A few particulars, which may be of interest, of the most important materials employed in the construction of these instruments, are appended. By the most important is meant, not those that enter most largely into the construction, but those on the constancy of whose properties the accuracy of the instrument depends.

Magnets.—Permanent magnets are used in type A instruments to supply the magnetic flux. Elsewhere they are used only for damping purposes. The form used for field magnets is more fully considered at page 38.

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TABLE IV.

—	Name of Steel.	Chemical Composition.	Coercive Force.	Residual Magnetism.
1	Assailly. . .	2·7% W, 1·10% C	68	500
2	Chatillon . .	2·7% W, 1·02% C	69	540
3	Boehler. . .	2·9% W, 1·10% C	74	530
4	Allevard . .	5·5% W, 0·59% C	72	560

In a paper on "The Magnetic Properties of Tempered Steel," in the "Bulletin de la Société d'Encouragement pour l'Industrie Nationale," Madame Curie arrives at the conclusion that for the best magnets, tungsten steels, properly hardened by quenching, should be used. Further she shows that in order to obtain permanency of strength they should be baked for about 48 hours at from 60°–70° C., and then partially demagnetised to the extent of about 10 per cent.

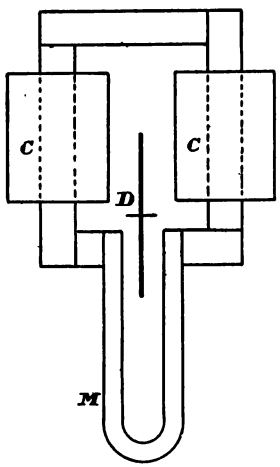

FIG. 33.

Magnets thus treated will remain constant in strength for a long time, and are practically unaffected by blows. A few of the tests on such steels are given above.

A common method used to produce permanent magnets is to fix the iron or steel to be magnetised to the poles of an electromagnet energised by a continuous current flowing through the coils C, see Fig. 33. In the gap between the poles of the magnet is pivoted a copper disc D. When the electromagnet due to the passage of a current becomes active, and the disc D is revolved, there are induced in this disc eddy currents. The effect of these eddy currents is such that the permeability for the space occupied by the disc is less than what it would be if no disc were there. The result is that the larger portion of the magnetic lines go along the

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path provided by the magnet M which is consequently strongly magnetised.

TABLE V.—PROPERTIES OF COMMON MATERIALS USED IN INSTRUMENTS.

—	Material.	Specific Resistance in Michroms per cm. Cube.	Temperature Coefficient per 1° C.	Composition.
1	Copper (annealed)	1·561	0·00428	Pure
2	Aluminium . .	2·762	0·00393	99·6Al, 0·14Si, 0·31Fe
3	Phosphor bronze .	16	0·00038	
4	Nickel steel . .	29·452	0·00201	4·35 per cent. Ni
5	German silver .	30·0 29·98	0·00036 0·000273	Cu 60·1; Zn 25·37; Fe 0·3; Ni 14·03
6	Manganin . . .	42	see curve (Fig. 34)	Cu 84; Ni 4; Mn 12
7	Eureka . . .	47·1	0·000005	
8	Platinum silver .	24·12 31·582	0·00031 0·000243	Ag 66; Pt 33
9	Constantan . .	48·6	0·000017	Cu 60; Ni 40
10	Brass	7·8	depends on composition	

—	Material.	Specific Resistance Mega Megohms per cm. Cube.
1	Mica	84
2	Micanite . . .	2,490
3	Shellac . . .	9,000
4	Black fibre . .	68
5	Ebonite . . .	28,000

1. *Copper.*—The standard resistance used for comparison is that originally formed by Matthiessen, and is the resistance of a copper wire 1 metre in length, 1 gramme in weight, at 60° F. This resistance is 0·150822 ohm for annealed high conductivity copper. The principal impurities which occur

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in this metal are arsenic and antimony, which should, as far as possible, be removed, as they seriously affect the conductivity. A percentage as low as 0·01 per cent. of arsenic and antimony, lowers the conductivity 0·5 per cent., while 0·03 per cent. lowers it as much as 9·5 per cent. It is now possible to obtain copper for commercial purposes at least 1 per cent. better than Matthiessen's standard.

2. *Aluminium.*—The purest aluminium met with in commercial work contains about 99·6 per cent. of the metal, with traces of iron about 0·31 per cent., and silicon about 0·14 per cent. Weight for weight it is about twice as good a conductor as copper, the density of the latter being 8·79 and of the former 2·6. It is for this reason that it is so largely used in the light movements so necessary in instrument work.

3. *Phosphor Bronze.*—This is an alloy of copper, tin and phosphorus, of a reddish brown colour, which after proper annealing and tempering possesses great resiliency, an indispensable requisite for springs. As a setback, however, to this desirable property it has a rather high temperature coefficient and great specific resistance, which is a disadvantage when, as is sometimes the case, the springs are used as conductors.

5. *German Silver.*—This is one of the oldest alloys possessing a low temperature coefficient. The constants given will vary somewhat largely for small variations in the composition as also do the colour and hardness. When exposed to the air for any length of time this alloy becomes very brittle. A copper and German silver junction has an average thermo-electric force of about 17 microvolts per 1° C. It is, however, being very largely superseded by manganin.

6. *Manganin.*—This is a soft material which readily oxidises in air. It was the outcome of a series of experiments carried out by Dr. Weston in 1888 in America, on the variation of resistance when manganese was added to copper. If heated at a temperature of 140° F. for about 5 hours in a bath, and prevented from coming into contact with the air by a coating of shellac, it is found that the resistance will then remain practically constant. The composition given in Table V. is the one found to give the smallest temperature coefficient

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which is not absolutely constant, but varies as shown in the curve, Fig. 34. Here the average temperature coefficient over 10° C. is plotted against the temperature.

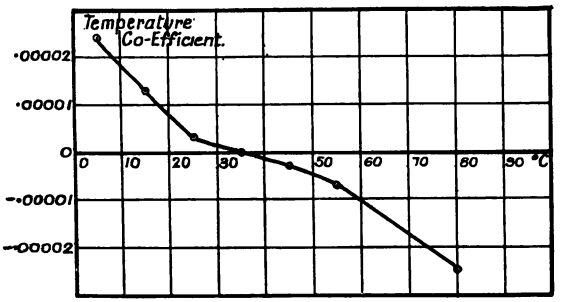

FIG. 34.

8. *Platinum Silver.*—This alloy is of a white colour and does not become oxidised when exposed to the air. It remains unaltered after undergoing baking and annealing processes, and has been found to remain constant in its electrical properties for a very long time.

9. *Constantan.*—This material possesses an advantage over manganin in that it can be heated up to 300° C. without affecting the constants; and further it resists oxidation even when heated to this high temperature. There is, however, one serious drawback to its use. Its thermo-electric force with copper is high, amounting to about 37 microvolts per 1° C., whereas that of manganin and copper is only 1·5 microvolt per 1° C.

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CHAPTER III.

MAGNETO-DYNAMIC PRINCIPLE.

MOVING COIL SYSTEM.

MOVING coil instruments made on this principle, page 3, are in consequence restricted in their use to the measurement of continuous currents.

These instruments consist of a permanent magnet and a small pivoted coil capable of rotation in the field of this magnet.

a, b. AMMETERS AND VOLTMETERS.

Though intended to measure distinct properties of the electrical circuit, the difference between their construction is so slight that, for the sake of brevity, they will hereafter be considered together.

Construction.—The magnet A, Fig. 35, usually takes the common horse-shoe form, or some slight modification of it, according to the necessity of the design, and is made of the best steel obtainable. The section is rectangular, and from $\frac{1}{2}$ to $\frac{3}{4}$ square inch in area, according to the range of the instrument. The steel found most frequently used for this class of work, is steel alloyed with different percentages of either tungsten or chromium, according to the experience of the makers, and tempered glass hard. The reliability of this instrument depends almost entirely upon the permanency of the magnet, which will be valuable in proportion to the length of time that it will retain its magnetism without loss. To obtain this essential quality the magnet has to undergo some process of magnetic soaking, in order that its strength may not diminish through lapse of time. There are various

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methods of accomplishing this result, but one of the simplest and most effective is that of Professors Strouhal and Barus, in which the steel is subjected to a steam-bath for from 20 to 30 hours, according to its volume. It is then fully magnetised and again replaced in the bath for another 5 to 8 hours. This process has the effect of producing in the magnet what it could only have acquired after several years, and is called "Artificial Ageing." The strength of field required from this

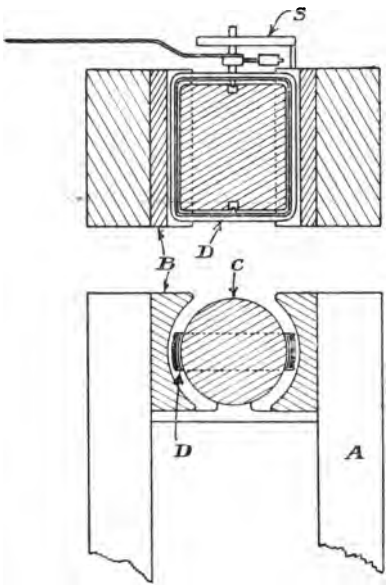

FIG. 35.

magnet, is proportional to the loss due to friction at pivots, air resistance, and weight of pointer and coil. The usual value of this field is from 1500 to 2000 lines per sq. cm., but instruments have been made with fields varying from 700 to 4500 lines per sq. cm.

To concentrate this field and make it as radially uniform as possible, there are fixed to the magnet two soft iron pole pieces B, shaped so as to leave an open circular space in the centre of which is fixed a soft iron core C, between which and

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the face of the pole pieces a narrow annular gap is left. The radial depth of this gap varies from 0·09 to 0·14 inch.

The moving coil D consists of a few turns of Nos. 31 to 33 S.W.G. double silk covered copper wire for ammeters, and about 2 layers of the same class of wire but of smaller gauge, Nos. 40–43, for voltmeters, wound on a slight framework generally of rectangular shape made of aluminium or copper. Some makers prefer the one, some the other, according to the object which they wish to obtain, aluminium giving lightness and rigidity, copper affording a greater damping effect and possessing greater plasticity. This coil is pivoted generally at the centre, but in some instruments at the ends of one side, so as to swing freely in the annular gap already described. The pivots are made of glass-hard steel, needle pointed, and with the finest polish obtainable, set in sapphire or agate sockets. Particular attention has to be paid to the surfaces here, in order to reduce friction-loss to a minimum. To balance the torque due to the magnetic fields, some kind of control, which usually takes the form of a spiral spring S, is needed. These springs are made of a non-magnetic material, generally phosphor-bronze, which remains practically constant in strength, and therefore produces no error due to ageing.

In order to lead the current on to and away from the coil, one end of the coil is connected to the metal spindle, and thence through the control-spring to the terminal. The other end of the coil is attached to a small non-conducting collet, usually of bone or ivory, on the spindle, where it is connected to a single loop of thin narrow copper strip, which produces almost no action on the control. Fig. 36 shows the method employed by Messrs. Crompton, Ltd., for leading the current into and out of the moving coil, in this case the strips B are composed of silver foil. The other end of the strip is attached to an insulated stud on the pole-piece, and thence the current flows through what is technically known as the "Swamp" (see page 44), to the other terminal.

A light metal stamping is attached by means of a collet to the spindle, which is used to carry the pointer and the counterpoise weights necessary to balance it.

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The scale is printed on thin Bristol card backed with zinc, and fixed as far as the length of the pointer allows from the centre of the coil so as to give as open a reading to the scale as possible. The angle subtended by the scale depends on the size of the instrument, but is from 60° to 75° for instruments having pointers 4 to 5 inches long. In instruments where an open scale near the working point is an advantage, springs are used which are already exerting a torque, thus preventing the needle from indicating until this torque is overcome; the effect of this is to lengthen the scale, but not in

FIG. 36.

any wise to affect the accuracy of the instrument. To indicate this modification the phrase "Set up" is prefixed to the name of the instrument.

These parts, the magnet, pole pieces, core, and moving coil, when assembled are known as the "movement," and are fixed to the pot or case through an insulator which serves the double purpose of insulating the movement and isolating the magnetic system when the pot is of iron. In this case the insulator separating the movement from the pot is usually from $\frac{1}{4}$-inch to $\frac{1}{2}$-inch thick, in order to reduce to a minimum any magnetic leakage from the permanent magnet to the pot.

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Theory.—Assuming that we have a magnetic field whose intensity is H lines per sq. cm., and that there is placed in it a wire of length l cm. carrying a current of C absolute units. Now let this wire be moved at right angles to the field through a distance x cm. in such a way as to cut the field. The area swept out by this wire will be equal to $l\,x$ sq. cm., and the number of lines cut to $H\,l\,x$. Now, since the wire is carrying a current of C units, the work done in cutting these lines will be equal to $C\,H\,l\,x$ ergs. But as in dynamics the work done by a force f, in moving its point of application through a distance x, is equal to $f\,x$ units of work, that is

$$\text{force} = f = \frac{\text{work}}{x}$$

and substituting above value for the work done we have

$$f = \frac{C\,H\,l\,x}{x} = C\,H\,l$$

acting in a direction at right angles to both the wire and the magnetic lines.

Applying the result just obtained for a general case to the particular case of a moving coil instrument, it will be found that, since for any instrument the length of wire l and the intensity of field H remain constant, the force varies as C. The current considered here is that flowing in the moving coil, and as this is made proportional to either the current or the voltage in the main circuit, so will the instrument become an ammeter or a voltmeter. The force, since it acts on a wire capable of rotating about a point becomes a torque, and is balanced by the torque exerted by the control spring. If the torque exerted by the spring is proportional to the angle turned through, that is D, then the scale will be evenly divided and $D \propto C$. In cases where the current to be measured cannot be wholly passed through the instrument, a part of it has to be shunted, and in order that the part flowing through the shunt may be proportional to the main current, the resistance of this part must be constant at all ordinary working temperatures. This may be obtained by inserting in the main

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circuit a shunt, see page 25. To the extremities of this section the terminals of the instrument are connected, see Fig. 37. In order to secure that the current in the moving coil may be proportional to the voltage in the main circuit, a large non-inductive resistance E R must be inserted in series with the instrument, across the mains, see Fig. 38.

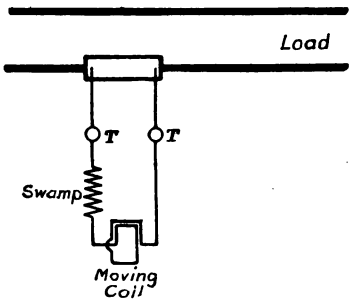

FIG. 37.

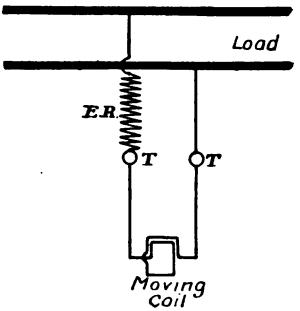

FIG. 38.

Errors.—Theoretically we have shown that the readings of the instrument are directly proportional to the current, but in practice it is found that certain defects in materials and workmanship are liable to bring in a number of small errors which have to be guarded against or allowed for. They are :—

1. Deterioration of spring.
2. Deterioration of magnet.
3. Temperature errors.
4. Stray magnetic fields.
5. Thermo currents at shunt terminals.
6. Alteration in resistance of connecting leads.

1, 2. By very careful manufacture and selection, Nos. 1 and 2 may be almost entirely avoided.

3. Temperature errors cannot be disposed of in the same way as numbers 1 and 2 because of the nature of the material used. It is found in the case of an ammeter that the ratio of the resistance of the copper winding on the moving coil to the total resistance of the instrument is nearly always large, so that variations in the resistance due to temperature changes

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are great. But this may be almost completely eliminated, by putting in series with the moving coil, a resistance about four times as large as that of the moving coil, and whose temperature coefficient is practically zero. This additional resistance is what is known as the "swamp," Fig. 37. This error amounts to about 0·4 per cent. for each 1° C. rise in temperature when no swamp is used, but with a swamp the error is reduced to 0·01 per cent. per 1° C. rise.

4. The error arising from stray magnetic fields, usually reckoned to amount to about 2 per cent. of maximum scale reading, may be avoided by efficiently shielding the movement. It is, however, generally found in practice that the ordinary cast-iron pot of a switchboard instrument is of itself sufficient to accomplish this.

5. If the shunt terminal blocks are of unequal surface, there will be, when a current is flowing through the shunt, a difference of temperature between the blocks due to one block radiating heat faster than the other. The E.M.F. set up in the shunt from this unequal heating is sufficient to cause an appreciable error which may sometimes rise to 2 per cent. maximum scale reading. The remedy for this is self-evident.

6. An error would arise if in connecting the instrument to the shunt, wires of greater or less resistance were employed than those used when the instrument was calibrated. This error is avoided by using standard leads.

These errors being thus, as far as possible, carefully eliminated, the instrument may now be relied on to read correctly to within 1 per cent. of the maximum scale reading.

The utility of the instrument is further enhanced in that it possesses certain advantageous features which may be stated as follows :—

1. That as the torque is always proportional to the angle turned through, the scale can be evenly divided and therefore very easily read. This is very well shown by Fig. 39, which is a "set up" voltmeter scale.

2. That the instrument is remarkably dead-beat, owing to the induction of eddy currents in the metal frame of the moving coil.

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3. That, because of the great intensity of the field used, the current required to work the instrument is small, and consequently the power-consumption is low.

4. This great strength of field allows for increased control without seriously affecting the great sensibility of the instrument, thus increasing its commercial utility.

5. Further, by reason of this increased control, less care need be taken in fixing the instrument perpendicularly.

6. And for the same reason its accuracy is not diminished when used in a portable form, if the instrument is properly shielded.

7. Since in this instrument the reversal of the current will give equal readings on either side of the "at rest" position, it may be calibrated as a central zero instrument. This renders it of value in the charging of accumulators.

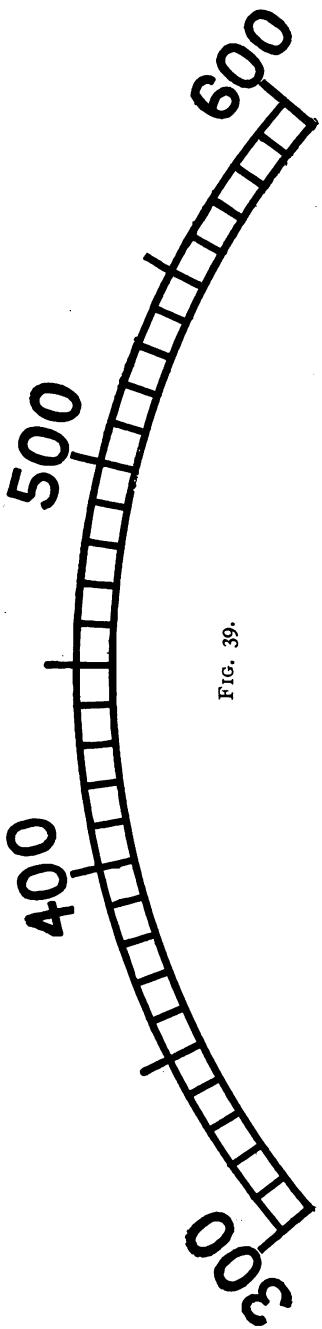

FIG. 39.

c. LEAKAGE INDICATORS.

If a cable is in a damp situation a considerable amount of leakage is almost certain to occur, and what is still worse small faults which, if neglected, will eventually develop into earth connections or shorts are sure to be augmented under such conditions.

Leakage from a cable may occur in two ways.

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1. Along its outside surface from bare connections, etc.
2. Through its insulating cover.

The amounts of these leakages are by no means equal. No. 1 will be greatest when the cable is short and in a damp place, and No. 2 when the cable is long.

As the result of the appointment of a committee by the Government in 1902, it is now ordered by the Home Office that the leakage current from any installation, so far as practicable shall not exceed 0·001 of the maximum supply current, and that daily records of the same must be kept.

The instruments, which have been devised to supply the demand created by this order, are usually milli-ammeters specially connected to the circuit.

Construction.—This is practically identical with that of a central zero voltmeter of this system described on page 38. The only difference which is likely to occur is that the winding of the moving coil may not be the same. As will be seen from the theory following, the best resistance for the instrument is that G should be equal to the combined fault resistance. This of course cannot always be the case, but for any instrument an approximation can be aimed at, and it is in order that this should be so that the winding may be altered. The connections do not differ greatly from those of a voltmeter. Across the mains, see Fig. 40, is connected a high resistance R (from 100 to 200 ohms per volt) of 50,000 to 100,000 ohms. The middle point B of this resistance together with the two ends A and C are separately connected to three studs of a switch. The common point P of the switch is connected to one terminal of the instrument, the other being connected through another resistance not nearly so large as R, to a good earth.

There is usually some device added to protect the instrument should a serious fault develop. This generally takes the form of a shunt circuit, or a fuse which blows when a certain current flows through the instrument, and thus cuts it out of circuit.

When a reading is not being taken the switch is left on the stud connected with B, so that the instrument will read the

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algebraic sum of the leakage currents, the pointer inclining to the one side or the other, as the one main is more leaky than the other. In order to take a reading, however, the switch is passed to stop A to test the resistance of the negative main, and similarly to C in order to obtain the resistance of the positive main. When the switch is on A or C, the resistance R is momentarily disconnected while the reading is being taken, in order that there may be no parallel path through the instrument for the leakage current from the main not under test.

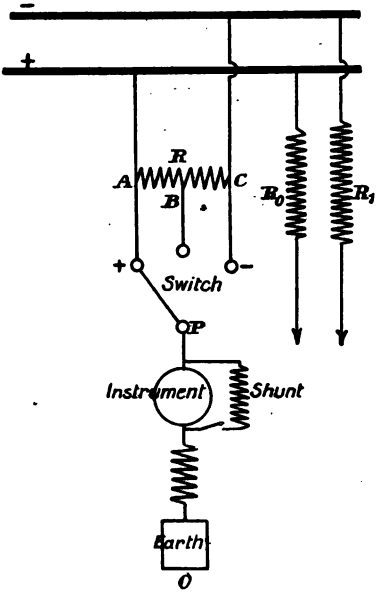

FIG. 40.

There is often used in conjunction with these instruments a bell, actuated by a relay inside the case, so that when a leakage current of a certain magnitude flows through the moving coil, the relay is closed and the bell rung, thus informing the attendant that a short has developed on the mains.

Theory.—The current flowing in a milli-ammeter is proportional to the voltage at its terminals, so that in the follow ing discussion the readings will be taken as in volts.

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Let

E = voltage of the mains,
V_0 = reading given by instrument when on stop C,
V_1 = reading given by instrument when on stop A,
G = resistance of instrument in ohms.

Now considering the point o in Fig. 40, when the switch is on stop A, it is seen that the current flowing to it

$$= \frac{V_1}{G} + \frac{V_1}{R_0}$$

and the current flowing from it

$$= \frac{E - V_1}{R_1}$$

$$\therefore \quad \frac{V_1}{G} + \frac{V_1}{R_0} = \frac{E - V_1}{R_1}$$

if

$$\frac{1}{F} = \frac{1}{R_1} + \frac{1}{R_0}$$

then

$$V_1\left(\frac{1}{G} + \frac{1}{F}\right) = \frac{E}{R_1} \quad . \quad . \quad . \quad (1)$$

If switch is now put on stop C, then

$$-\frac{V_0}{G} - \frac{V_0}{R_1} = \frac{E - (-V_0)}{R_0}$$

$$\therefore \quad V_0\left(\frac{1}{G} + \frac{1}{F}\right) = -\frac{E}{R_0} \quad . \quad . \quad . \quad (2)$$

subtracting (2) from (1)

$$(V_1 - V_0)\left(\frac{1}{G} + \frac{1}{F}\right) = \frac{E}{F}$$

whence

$$F = G\,\frac{E - (V - V_0)}{V_1 - V_0} \quad . \quad . \quad . \quad (3)$$

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From (2) $$R_0 = -\frac{E}{V_0\left(\frac{1}{G} + \frac{1}{F}\right)}$$

and substituting the value of F as given by (3) in this equation

$$R_0 = -\frac{G\{E - (V_1 - V_0)\}}{V_0}$$

and in a similar way from equation (1)

$$R_1 = \frac{G\{E - (V_1 - V_0)\}}{V_1}$$

the leakage current

$$= \frac{E}{R_0 + R_1}$$

$$= \frac{E\,V_1\,V_0}{G\{E - (V_1 - V_0)\}\{V_1 - V_0\}} \quad . \quad . \quad (4)$$

Any instrument in which the deflections are proportional to the current may be substituted for the one used here, in which case, however, if

D = deflection proportional to E
d_1 = deflection proportional to V_1
d_0 = deflection proportional to V_0

then

$$R_0 = -\frac{G\{D - (d_1 - d_0)\}}{d_0}$$

and

$$R_1 = \frac{G\{D - (d_1 - d_0)\}}{d_1}$$

From these formulæ it is possible to calculate the leakage resistances of the mains. In order to avoid this calculation, however, a table is usually supplied with the instrument from which, having the readings of the instrument, the resistances may be obtained.

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Errors.—These will be the same as for the voltmeter or ammeter of this type and need not be reconsidered here.

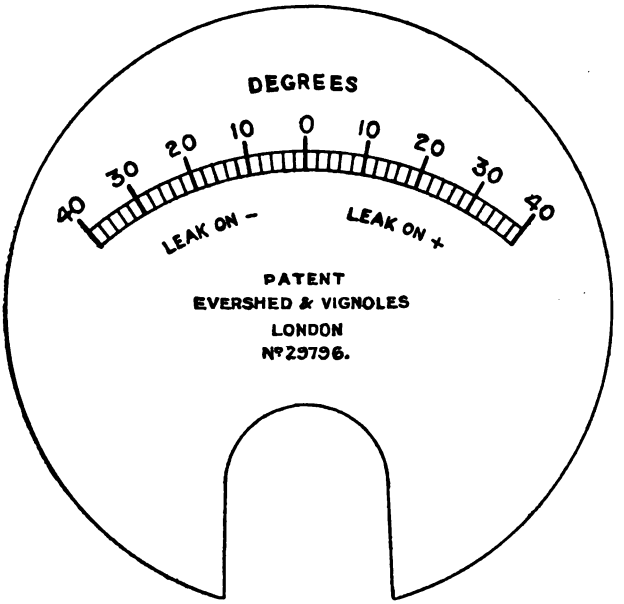

FIG. 41.

In Fig, 41 is shown a scale of one of these instruments which indicates the arrangement usually adopted.

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CHAPTER IV.

ELECTRO-DYNAMIC PRINCIPLE.

MOVING COIL SYSTEM.

THIS type of movement is used in nearly all the standard ammeters, such as Siemens's dynamometer, Kelvin's balances and Weber's dynamometer, but it is also largely used in practice, in such instruments as wattmeters, phasemeters and instruments intended for alternate current work generally.

From the construction of this instrument it follows that the magnetic fields are much weaker than in the permanent magnet type, described on page 38, the greater part of whose magnetic path is iron. Until quite recently it was thought that in alternate current instruments of this system no iron could be used because of the errors introduced by it. But Dr. Drysdale, Dr. Sumpner and others have shown that, by accurate design and careful construction, it is possible to employ iron in this type of instrument and still have accurate readings. In what follows, it has been found advisable to separate this system into two classes: (1) Air-core, (2) iron-core.

a, *b*. AMMETER AND VOLTMETER. AIR-CORE.

Construction.—The ordinary form of electromagnet employed consists of two fixed current-coils, each wound as a narrow cylinder whose diameter is from five to eight times its width, having their long axes parallel, and their short axes in the same straight line, see Fig. 42. They are separated by a slab of ebonite or fibre, which has the central portion removed so as to leave the air-core of the coils continuous. Sometimes the separator is dispensed with, leaving an air space the axial

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dimensions of which are small compared with the diameter of the coil. For ammeters these coils are wound with a wire whose section is sufficient to carry the current to be measured, but for voltmeters a wire of much smaller section is required, usually a No. 36–40 S.W.G. The number of turns of wire required varying as the strength of field which the maker purposes to use in the instrument. These coils may be connected either in series or in parallel, but so that the current flows in the same direction in both. In the case of ammeters, Fig. 43, this combination is put in one of the mains, but in that of voltmeters, Fig. 44, it is put across the mains.

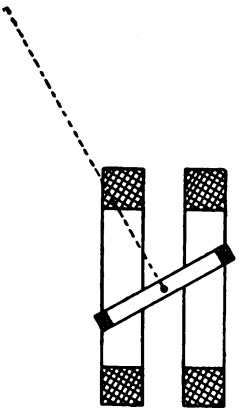

FIG. 42.

The moving coil, which must be of circular shape, cannot be wound on a metal frame because of the effect of the eddy currents in it on the strength of the field, but it may be wound on one of wood or ebonite though it is more frequently found without a frame, the wires being retained in their position

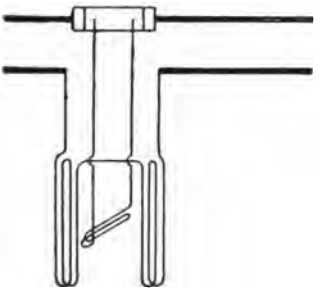

FIG. 43.

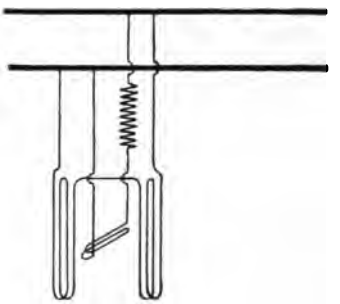

FIG. 44.

by an external binding of tape. The external diameter of this coil is governed by the internal diameter of the fixed coils, the clearance being reduced to a minimum. This coil is pivoted and connected on similar lines to those used in type A,

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page 40. The size of wire used is similar to that of type A ammeters.

Since it is inadmissible to use a metal frame, some form of damping must be provided, in this case, No. 1 or 2*a*, page 24. The opening, pointer, balance weights and pot are also as type A, but the scale is fixed on wood in preference to metal, to avoid the possible effects of eddy currents.

Theory.—As shown on page 42, $f = C H l$, where

f = force in dynes.
C = current flowing in moving coil in absolute units.
H = intensity of field in lines per sq. cm.
l = length of wire in cm.

As before l is constant, but now H is proportional to C and must be in phase with it.

$$\therefore \qquad f \propto C^2$$

The indications of the instrument will therefore always be positive.

Now since this force acts on a wire capable of rotation, it may be considered as a torque, but this torque is resisted by that of a spring, the torque of which is proportional to the angle turned through.

i.e. torque $\propto$ D, where D = deflection.

and $\therefore \qquad D \propto C^2$

i.e. $C = K \sqrt{D}$ where K = constant of the instrument.

Errors.—Trouble may be experienced from one or more of the following causes of error :—

1. Deterioration of spring.
2. Self-induction in the moving coil.
3. Temperature changes.
4. Stray magnetic fields.
5. Varying frequency.
6. Eddy currents.

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1 and 3. The errors arising from these sources are the same as those which occur in type A, page 43, and may be corrected in a manner similar to that already described there.

2. Self-induction in the moving coil circuit causes the current flowing in it to be slightly less than it ought to be, due to the choking effect. It also introduces into this circuit a lag which further reduces the effective torque. In order to remove, as far as possible, the error due to self-induction, the time-constant (i.e. ratio of self-induction to resistance) must be made as small as possible. This may be done by increasing the resistance of the moving coil, or preferably, by putting in series with it a resistance many times greater than its own, which has already been done, when putting in the external resistance in the case of voltmeters, and when putting in the swamp in the case of ammeters, if these are non-inductive as they should be.

4. Since the intensity of field usually employed in these instruments is about 50 lines per sq. cm., it can be seen that efficient shielding is absolutely necessary in order to get accurate readings. If the instrument is not situated on a switchboard in the presence of strong fields such as are generally met with there, it will be found that the iron pot is sufficient protection. But in most other cases it is better to have a double screen of iron enclosing the movement.

5. Since the self-induction of the moving coil is generally different from that of the fixed coil, variations in frequency will produce a small error which will diminish as the self-inductions are made negligible. For most practical purposes this error may be entirely disregarded.

6. Errors due to the presence of eddy currents may be reduced by removing, as far as possible, from the moving coil such masses of metal as may affect it. For this reason some makers prefer using non-metallic cases instead of the iron pot mentioned above, but if the iron case is well designed, so that no part of it is very near the moving coil, it will be found that little error is caused by eddy currents in it, see Fig. 10.

It may be mentioned in connection with this, that errors may often be found in heavy current instruments of this

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system, due to eddy currents being set up in the conductor, caused by the unequal distribution of current in it. When trouble of this kind is experienced, it is better to use coils capable of carrying a current of from 5–10 amps. and a step-down current transformer.

Advantages.—This class of instrument occupies the same place in relation to alternating currents that type A holds with respect to continuous currents and possesses the following among other advantages, viz.: that although designed as an alternating current instrument, it will work with equal precision on continuous current circuits.

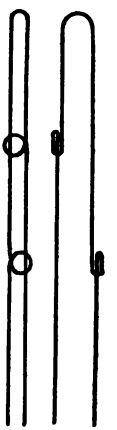

FIG. 45.

Disadvantages.—Against its good points must be put the following two drawbacks :—

1. Since the instrument follows a square law, the scale is unequally divided and consequently more difficult to read.

There is a very neat device employed by the Keystone Electrical Instrument Co., of Philadelphia, for improving the scales of instruments belonging to this system. It consists of a spring made as shown in Fig. 45, the action of which is such that it assists the ordinary spiral spring over the lower part of the scale, and resists it when the needle is moving over the upper part. It is easily seen that for small values of the current the controlling force will also be small,

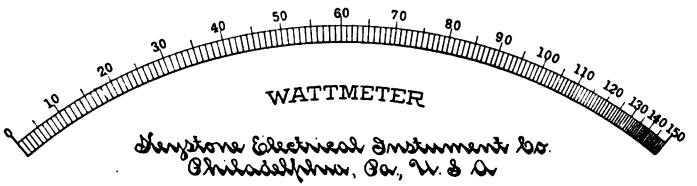

FIG. 46.

whilst as the deflecting force increases so will this additional spring automatically increase the controlling force, with a result that the spacing of the scale will be much more nearly uniform than in instruments without this device. The

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result obtained by the use of this patent is shown in a much better way by a comparison of the scales obtained with and without it. Fig. 46 is the scale of an instrument controlled by two spiral springs, and Fig. 47 the scale obtained, when this device was employed in conjunction with these springs.

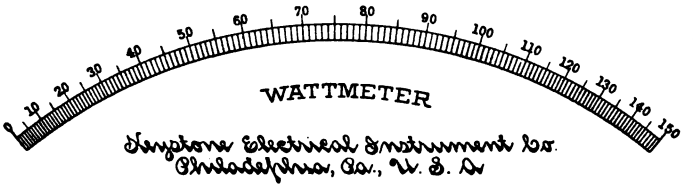

FIG. 47.

2. Its great weakness of field which renders it liable to external influences and reduces its sensibility.

a, b. AMMETER AND VOLTMETER. IRON-CORE.

Construction.—The iron-core instruments introduced by Dr. Sumpner differ from those just described in that the main coils are wound on an iron-core, and are provided with a nearly complete iron yoke, in which a small gap is left for the moving coil to swing in. The gap is so placed that the yoke may also be used as the iron-core for the moving coil. On account of this improvement, a slight modification has to be made in the connections of the voltmeter, the moving coil being connected across the mains through a condenser in order to bring the flux due to the moving coil current into phase with the flux due to the main coil current.

Theory.—This is the same as that given for the air-core instrument, page 53, with the exception that additional errors due to the presence of iron are introduced. They are caused by—

7. Varying permeability and with it varying leakage coefficient.
8. Hysteresis.
9. Resistance of magnetising coil.
10. Eddy currents in the iron.

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The errors already mentioned under air-core instruments still occur and are compensated for as above, page 53.

7. The direct error due to variation of the permeability of the iron is largely counterbalanced by the presence of an air gap. The ratio of the reluctance of the air gap to the reluctance of the iron path is great, hence, any alteration of the latter due to a change in the permeability will mean only a small change in the total reluctance, consequently the magnetic flux would remain practically constant. But a more serious error is introduced due to an indirect effect of this varying permeability, viz. alteration in leakage coefficient. Though as far as an ammeter or voltmeter is concerned this error (No. 7) is of no importance, since for the different currents and voltages measured, the moving coil must be in a different part of the gap, yet in the case of wattmeters it requires very careful attention. The only effect produced in ammeters and voltmeters is a slight alteration in the calibration of the instrument.

8. The iron used in these instruments will produce a hysteresis error which has the effect of throwing the flux out of phase with the current producing it. This error may be reduced by using very good iron, and by diminishing the ratio of the reluctance of the iron path to the reluctance of the air path where permissible. But it is found that for ammeters this error cancels out in a most remarkable manner. In the case of the voltmeter it is also negligible since the flux is proportional to the voltage, the magnetising current having to adjust itself to the flux produced by this voltage.

9. The magnetising coil must be so designed as to reduce the copper drop to a minimum, otherwise a phase error comes in. In order to make this voltage drop small compared with the voltage of the mains, the inductance of the magnetising coil should be proportionately increased.

10. If the iron is carefully laminated, the error due to this cause may be made inappreciable.

Advantage.—The design of this instrument is intended to remove the chief defect of the air-core class, viz. its great weakness of field, and this it effectually does.

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Disadvantage.—These instruments possess the disadvantage (if it may be so called) that the voltmeter cannot be used on continuous current circuits, but the ammeter might be, although in this case it could not be considered as an accurate instrument, owing to hysteresis.

c. WATTMETERS. AIR-CORE.

Construction.—This instrument is built on similar lines to the ammeter or voltmeter of this type, but is differently connected to the circuit. The fixed coils are joined in series or in parallel, and carry the main current as before, but the moving coil is put in series with a large non-inductive resistance and connected across the mains, so that the current flowing in it is proportional to the voltage, see Fig. 48.

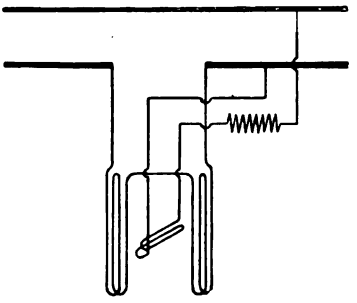

FIG. 48.

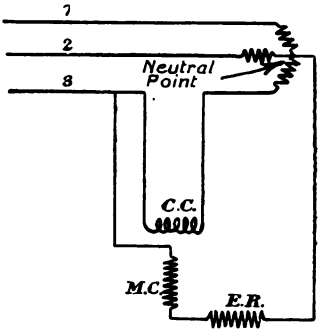

FIG. 49.

In order to measure the power in a two-phase supply however, two wattmeter readings are necessary. The wattmeter is connected across one phase first, then across the other, the sum of the readings giving the total power.

For a three-phase balanced load system it is sufficient to connect the current coil in one main and the moving coil between the neutral point and the main in which the current coil is fixed, see Fig. 49. If the moving coil is connected as there shown, the instrument reading will include the watts consumed in the current coil. If, on the other hand, the moving

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coil be connected on the other side of the current coil, then the reading will include the watts used in the moving coil circuit. Of the two, there is not much to choose between them, some prefer the one, some the other.

If the neutral point is inaccessible, then the moving coil must be inserted in one arm of a star resistance connected across the mains, see Fig. 50.

The three arms of the star must be of the same resistance, otherwise the proportion of volts in each arm will not be correct.

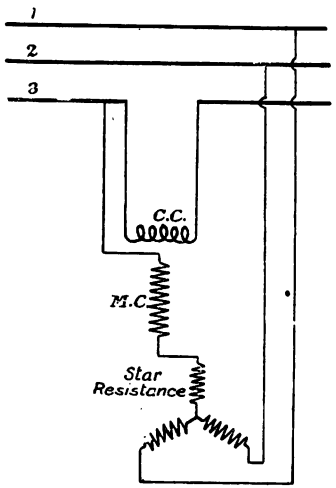

FIG. 50.

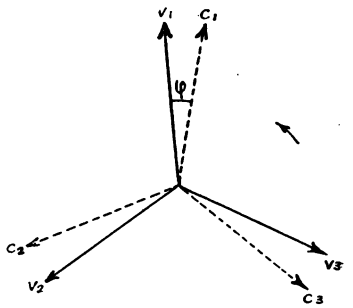

FIG. 51.

The currents flowing in the three phases may be represented by the vectors c_1, c_2, c_3, in Fig. 51, the projection of which on any axis will give the instantaneous value of the currents. The voltage in each phase may also be represented by three vectors v_1, v_2, v_3. The current lags behind the voltage by an angle ϕ. From the connections already given, Figs. 49 and 50, it follows that the current in the current coil will be represented by c_3, and the voltage in the moving coil by v_3, consequently the power measured by the instrument will equal $v_3 c_3 \cos \phi$. It is easily seen that this is one-third of the total power in the circuit, and as a result, the wattmeter reading

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has to be multiplied by three, in order to get the total power in the circuit.

When the load is unbalanced, two wattmeters are necessary. These are connected, as shown in Fig. 52. Sometimes these two wattmeters are combined into one case, the moving coils being fixed to the same spindle. The points A and B in the figure may then be joined together, only three connections to the mains being necessary. As in the previous case, c_1, c_2, c_3, and v_1, v_2, v_3, in Fig. 53, represent the currents and voltages in each phase. The vector difference of v_1 and v_3 will give

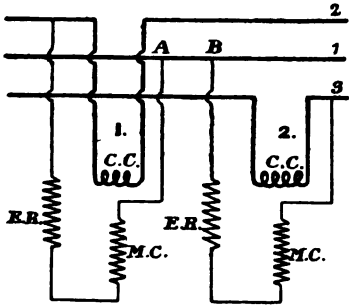

FIG. 52.

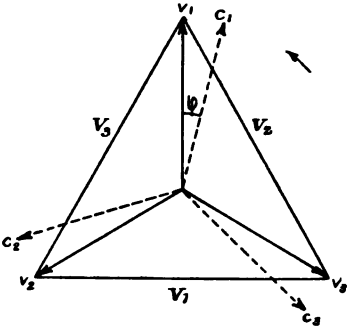

FIG. 53.

the voltage V_2 across the mains 1 and 3 and similarly V_1 and V_3 represent the voltages across mains 2 and 3, and 1 and 2 respectively.

Now the currents flowing in the mains at any instant have the following relation.

$$c_1 + c_2 + c_3 = 0 \quad . \quad . \quad . \quad (1)$$

and the total power

$$W = v_1 c_1 \cos \phi + v_2 c_2 \cos \phi + v_3 c_3 \cos \phi$$

From (1)

$$c_1 = -(c_2 + c_3)$$

$$\therefore \quad W = \{v_2 c_2 + v_3 c_3 - v_1 (c_2 + c_3)\} \cos \phi$$

$$= \{c_2 (v_2 - v_1) + c_3 (v_3 - v_1)\} \cos \phi$$

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but

$$v_2 - v_1 = V_3$$

and

$$v_3 - v_1 = -V_2$$

$$\therefore \quad W = \{V_3 c_2 - V_2 c_3\} \cos \phi$$

Now it is seen from Fig. 52 that wattmeter No. 1 will read $V_3 c_2 \cos \phi$, and wattmeter No. 2, $V_2 c_3 \cos \phi$, so the difference of the two wattmeter readings in the one case, or, if the instrument is a combined one, the reading on the scale in the other, will give the total power.

When two wattmeters are separately connected as mentioned on page 60, it is sometimes found that one wattmeter reads negative. This occurs when the power factor of the mains to which the wattmeters are connected is below 0·5. In Fig. 53, if v_1 and c_1 coincide, that is, if the power factor be unity then between the current in one main and the voltage between the mains, there is a lag or lead of 30°, as the case may be. If the angle of phase difference in the main circuit is 60° or more, it is easily seen that the reading must be negative.

Theory.—As shown on page 42, force $\propto$ C H, but the current flowing in the moving coil is proportional to the voltage V_1 of the main circuit, and H is proportional to C_1, the current flowing in the main circuit.

$$\therefore \quad \text{force} \propto V_1 C_1$$

As before, this force may be looked upon as a torque balanced by the control spring, the torque of which is proportional to D—

$$\text{i.e. torque} \propto D$$

$$\therefore \quad D \propto V_1 C_1$$

that is, the instrument reads direct in watts, but this is only true when the current is in phase with the voltage. If the current lags or leads with respect to the voltage, the current vector must be resolved into its two components, one in phase with V_1 represented by O L, the other 90° behind this repre-

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sented by O W in Fig. 54. But the product $O V_1$, $O L = O V_1 O C_1 \cos \phi$, where ϕ is the angle between the current and voltage vectors, and by definition the angle of phase difference. This product represents the effective torque, therefore the torque $= O V_1 O C_1 \cos \phi = V_1 C_1 \cos \phi$, hence

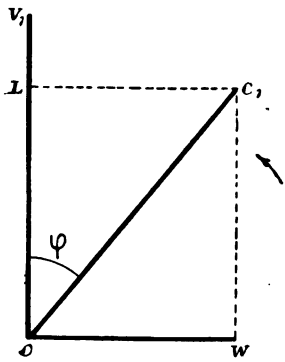

FIG. 54.

$$D \propto V_1 C_1 \cos \phi$$

Errors.—The correct reading (T) of this instrument should be $= V_1 C_1 \cos \phi$, but if there is a phase error produced in the moving coil, then the instrument will give a reading (A) $= V_1 C_1 \cos (\phi - \theta)$ where θ is the assumed phase difference between the voltage and the moving coil current.

Now the error expressed as a ratio of the true reading, is

$$e = \frac{A-T}{T}$$

$$= \frac{V_1 C_1 \cos (\phi - \theta) - V_1 C_1 \cos \phi}{V_1 C_1 \cos \phi}$$

$$= \frac{\cos (\phi - \theta) - \cos \phi}{\cos \phi}$$

$$= \tan \phi . \theta$$

where θ is small and is expressed in radians. For low power factors tan ϕ will be large, consequently θ has to be kept very small, if the instrument is to be made accurate. For instance, if with a power factor of 1·0 and a load of 100 volt amperes, we have a phase error θ of 0·01 radian we get a value of tan $\phi . \theta$ of say 0·1 per cent., but if we have a power factor of only 0·1 with the same phase error and same load, tan $\phi . \theta$ becomes 9·9 per cent.

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Looking at this error from another point of view, it has already been shown that A

$$= V_1 C_1 \cos(\phi - \theta)$$
$$= V_1 C_1 (\cos\phi \,.\, \cos\theta + \sin\phi \,.\, \sin\theta)$$
$$= V_1 C_1 \cos\phi \,.\, \cos\theta + V_1 C_1 \sin\phi \,.\, \sin\theta$$
$$= V_1 C_1 \cos\phi + V_1 C_1 \sin\phi \,.\, \theta \text{ when } \theta \text{ is very small.}$$

It is seen that the first term of this result is the true watts, consequently the second may be looked upon as the error in watts at that load, if $\theta = 0{\cdot}01$ radian, then this cannot exceed 1 per cent. of the reading.

The errors which this instrument suffers from are identical with those of the air-core ammeter or voltmeter, page 53. But if the accuracy is to be kept within 1 per cent., then very careful attention must be given in order to reduce the errors to negligible quantities.

It might be expected that an error would be introduced by mutual induction between the fixed and movable coils. Provided the self-induction is absent or very small, it can be shown that the error introduced from this source will be negligible. The E.M.F. induced in the moving coil by the main coil flux will lag 90° in phase behind it, and consequently, if the induced current is in phase with the E.M.F., the torque exerted between this flux and current will be nil.

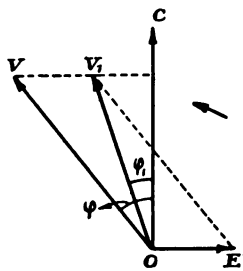

FIG. 55.

This can be shown very simply by means of a vector diagram, see Fig. 55. If O C represents the flux vector due to the main coil current, then O E will represent the induced E.M.F. in the moving coil, and if O V represents the terminal voltage leading by an angle ϕ, the resultant voltage in the moving coil will be O V_1 leading by angle ϕ_1. Now the true power is the product of the current and the component of the voltage in phase with it, and it is easily seen that the components of O V and O V_1 in phase with O C are the same,

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consequently the power given by the instrument will be independent of mutual induction, if no self-induction is present. In Fig. 56 has been plotted the coefficients of mutual induction found to exist between the fixed coil which lay along the line 0°–180° and the moving coil when it lay along the lines 0°–30°, 0°–60°, etc. respectively.

There is, in addition to those already enumerated, another source of error, unimportant in the earlier instruments, but which cannot be neglected here, it is that due to

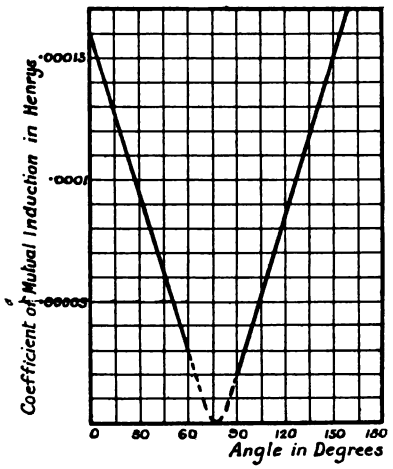

FIG. 56.

7. Capacity in the moving coil circuit.—When two conductors situated near together, but separated by a good insulator, are carrying an alternating current, displacement currents are set up across this insulator. These currents have a similar effect to that obtained when a condenser is shunted across the terminals of the moving coil circuit, and cause the reading to be greater on a leading load and less on a lagging load than the true value obtained on a non-inductive load. The error produced by capacity, which is principally seated in the non-inductive resistance, may be reduced by dividing the winding into sections, the capacity being proportional to the inverse square of the number of sections.

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Instruments of this type may be used for currents up to about 200 amps., above this value the current in the fixed coil must be taken as a shunt from the main circuit, or from a series transformer, since at this amperage the effect of eddy currents in the conductors forming the fixed coil begins to become serious.

The advantages and disadvantages are the same as for the ammeters and voltmeters of this type.

c. WATTMETERS. IRON-CORE.

Construction.—This instrument is similar in construction to the iron-cored voltmeter or ammeter, see page 56. The magnetising coil may be connected (1) in series with one of the mains, in which case the moving coil has to be connected across the mains through a high resistance. But it has been found that with these connections the errors introduced by the iron-core are so large that in endeavouring to overcome them the advantages gained by using iron are greatly reduced. (2) It may also be connected as a shunt to the main circuit, then the moving coil must have a current flowing in it which is proportional to the main current, but in quadrature with it, see Voltmeter, page 56. The current in the moving coil is usually supplied from the secondary of a small air-core transformer connected in series with a high non-inductive resistance. The primary of the transformer is placed in one of the mains.

Theory.—The theory is the same as for the air-core instrument already described, and the error is as before $e = \tan \phi \, . \, \theta$. The errors which are to be found in this instrument are similar to those mentioned in connection with iron-cored ammeters and voltmeters. As explained in the air-core wattmeter, the errors must be kept exceedingly small, if the instrument is to be accurate. The care which was used in that case in eliminating them must be quite as rigidly applied in this case, if anything approaching 1 per cent. accuracy is hoped for.

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d. PHASEMETER. AIR-CORE.

In an alternating current system where the current provided by the generator is not in phase with the voltage, there is an imaginary component of this current which does no work. This component, known as the "wattless current" is in quadrature with the voltage, and increases inversely as the power factor. It is considered by some that it is more important to know the wattless component of the current than

FIG. 57.

the power factor, since the greater this current becomes the larger will be the armature reaction, and consequently the worse will be the regulation of the alternator. On the other hand, it is contended that it is of greater utility to know the power factor, as this affords the means of estimating the effective work being done in the system.

Let us consider first the instruments used to measure the

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power factor, leaving those for measuring the wattless component to be dealt with later.

This type of instrument, an external view of which is shown in Fig. 57, may be made up of a combination of from three to six coils, depending upon what system it is to be used upon.

Construction.—One coil is fixed and is similar in winding, size, shape, and method of fixing, to that described under type B_1 ammeters, page 51. This coil is usually divided into

FIG. 58.

two halves placed in series, and separated by a sufficient distance to allow the movement to be placed between them. A fair idea of the internal construction of this instrument is given by Fig. 58, which shows construction adopted by Messrs. Everett, Edgcumbe and Co.

The moving coils must of course be wound on non-metallic frames of a circular shape, and usually consist of a number of turns of fine wire similar in size to that used for type A am-

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meters, page 52. These coils are fixed to the same spindle at an angle to one another, the magnitude of the angle which gives the best scale requires to be found by experiment. This spindle is pivoted in a similar fashion to that used for type A ammeters or voltmeters. No control spring is needed in any of the instruments described below. The reason for this will be evident from the theory. Since it is desired to measure a 90° lag or lead, it is necessary to have a scale opening of at least 200°. The construction of scale is similar to that used for type B_1 ammeters.

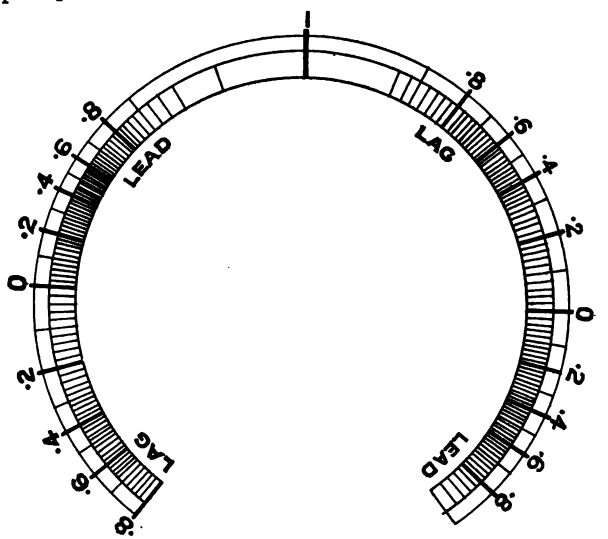

FIG. 59.

In Fig. 59 is shown the scale of a single-phase instrument and in Fig. 60 that of a three-phase one. In both cases it is seen that the scale closes up very rapidly from 1 to 0, and that in the three-phase instrument the divisions are shortest about a P.F. 0, whereas in the single-phase instrument they are shortest about a P.F. 0·5.

Phasemeters have been constructed to take a current of 100 amps. at 500 volts directly through the field-coils, but it is now a common practice to use transformers in order to step the current down to from 5–10 amps. For voltages above 500, it

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is found advisable to use potential transformers, otherwise great difficulty is experienced in properly insulating the coils.

Connections, Single-Phase.—The moving coils, when the instrument is intended for a single-phase system; are connected up as follows : Two of the four ends of the moving coils, one of each, are joined together and the common junction J, Fig. 61, connected to the metal spindle from which is taken a thin flexible copper loop fixed to an insulated stud. The other two ends are brought from the moving coils to two insulated col-

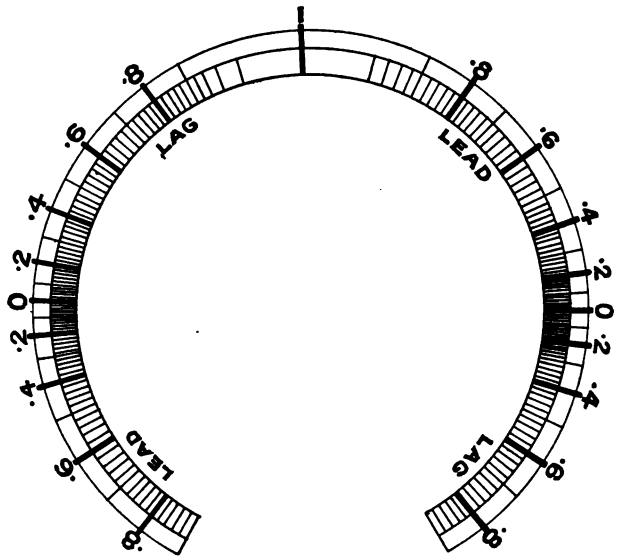

FIG. 60.

lets fixed to the spindle, where they are attached to two insulated studs by flexible loops as before. The three insulated studs are now connected to three terminals of the instrument, one of which, viz. the one to which the common junction of the moving coils is attached, is connected to one main of the system. The other two terminals are brought to two terminals of a resistance box, containing two branches, one of which consists of a high non-inductive resistance R, the other of a high inductive resistance I, the two ends of these resistances

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are joined together, and the common junction J_1, brought to a third terminal of the resistance box; this third terminal is connected to the other main.

Two-Phase.—When the instrument is designed for a two-phase circuit, the connections are made as follows. The coils are kept separate, the four ends being brought to four insulating collets fixed to the spindle, and there attached to four flexible loops, the other ends of which are fixed to insulating studs. These studs are then connected to four terminals of the instrument and thence through high non-inductive resistances to the mains, so that the moving coils are respectively

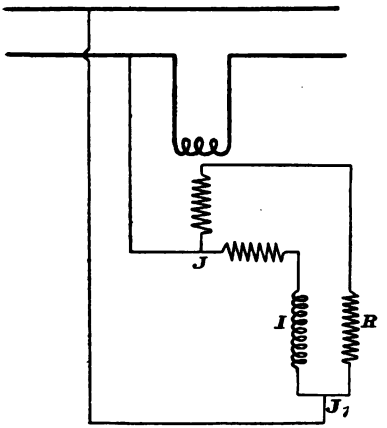

FIG. 61.

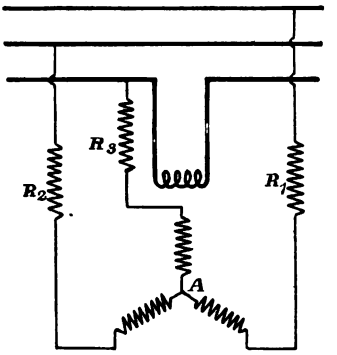

FIG. 62.

put across each phase. These resistances may be placed, half in the outgoing, and half in the return path of each moving coil, but more often they are put in the one side or the other.

The angles between the moving coils used for the instruments just described are approximately 90°.

Three-Phase.—For three-phase circuits there is a slight modification made in the above construction, instead of using two moving coils, three are now employed, two fixed coils still being used. These moving coils are symmetrically placed, at angles of 120° to each other, about the spindle, and are usually wound on a sphere of non-metallic material, such

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as fibre, wood, etc., in which narrow slots are cut to hold the wire in position, the size of wire used being the same as before. One end of each of these coils is connected together, A, Fig. 62, the other three ends being connected to the terminals of the instrument by flexible loops as described above. These three terminals are then connected through high non-inductive resistances, R_1, R_2, R_3, to the three mains, thus putting the coils across the phases.

These instruments can only be used when the load on each phase of the system is the same, that is when the load is a balanced load. In cases where the load is unbalanced it is necessary to have a current or fixed coil in each phase as well as a moving coil across each phase.

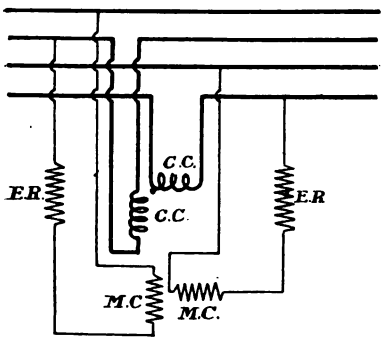

FIG. 63.

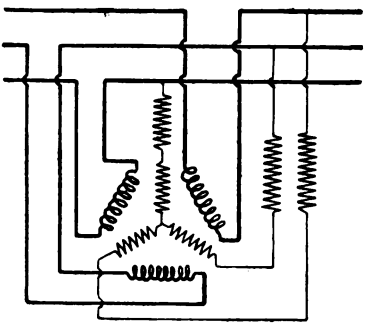

FIG. 64.

In two-phase unbalanced circuits, instead of having the two halves of the fixed coil both placed in the one phase, they are now put one in each phase, and placed at right angles to one another while the moving coils, constructed as before, are placed across each phase, see Fig. 63.

For a three-phase system, however, three fixed coils are necessary. They are symmetrically placed to one another, see Fig. 64, with an angle of 60° between their vertical planes, but an angle of 120° between their magnetic axes, and are fixed, so that the space between them is as small as possible. The moving coils are pivoted in the centre of this space, and

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are constructed exactly as described for the balanced load instrument.

FIG. 65.

FIG. 66.

There is a slight modification of this construction employed in the Westinghouse power factor meter, an internal view of which is shown in Fig. 65. In this instrument both

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the coils are fixed. The movement consists of a light iron vane situated in such a position as to be affected to about the same degree by both coils. It can easily be seen from the theory that this vane will be subjected to the same forces as the moving coil in the construction just considered. An external view of a portable instrument of this class is shown in Fig. 66. This instrument is for use on a three-phase system, and shows that the scale given by this modification does not differ greatly from that obtained by the normal construction, as shown in Fig. 60.

Theory.—If two equal alternating fields of the same frequency be produced by two alternating currents, passing through two coils placed at an angle to one another, a rotating magnetic field of the same frequency as its components will be produced, provided that the phase difference between the two currents is equal to the supplement of the angle between the coils carrying the currents. This is true also for three alternating currents passing through three coils placed in accordance with the conditions.

1. *For Balanced-Load Instruments.*—From the proposition just given it follows that the currents flowing in the moving coil will give rise to a rotating field of the same frequency as the currents themselves, whereas the field set up by the main coil will simply be an alternating field. In Fig. 67, if O M represents the maximum value of the alternating field given by O M sin $p\,t$, and O R the position of the rotating field (whose magnitude is a constant) at the instant of maximum main field, and if ϕ be the angle between these vectors, then the force exerted between the fields will be proportional to O R . O M sin $p\,t$. cos ϕ, and since the rotating field is produced by a movable system, the main field system being fixed, it follows that this force will tend to pull O R so as to coincide with O M. In Fig. 67, the small arrows indicate the directions in which the force pulls in the different quadrants, and it can be readily seen that F_2, F_4, F_6, F_8, balance one another, the remaining forces F_1, F_3, F_5, F_7, all pulling O R into line with O M. Suppose that O R is pulled so as to coincide with O M when at a maximum, then F_1, F_3, F_5, F_7, vanish, and the balance between

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the others remains undisturbed. If f is the frequency of the circuit, then these pulls will vary four times as fast as f, and consequently the resulting motion of the moving system will be nil, owing to the large moment of inertia of the moving coils. Now since the current in the main coil is, or is proportional to, the main current, and the currents in the moving coils are made proportional to the voltage, any lag or lead in the main current will cause the maximum value of the main field to occur after or before the axis of the rotating field coincides with the axis of the main field. When this occurs, a pull tending to make the axes coincide is created, and consequently

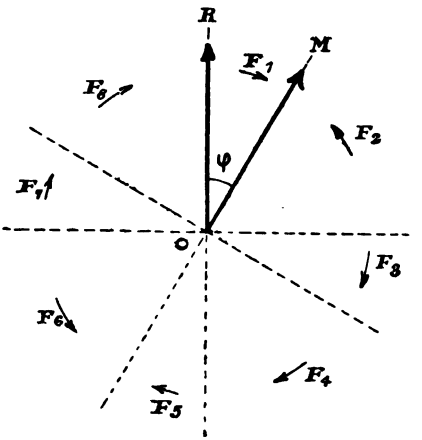

FIG 67.

the moving system moves through the angle ϕ between the axes, that is the angle of lag or lead. If, therefore, a pointer is attached to the moving system, it will directly indicate this angle, and thus become a phasemeter.

2. *For Unbalanced-Load Instruments.*—When these instruments are designed for unbalanced loads according to the principle enunciated above, there are produced two rotating fields, one by the fixed coils, the other by the moving system. If the axes of these two rotating fields are coincident, no torque will be exerted on the moving system, as the fields are both rotating at the same rate. But if one field shifts its axis with respect to the other by an angle ϕ, then the moving system

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will experience a torque, and will rotate till the axes of the two fields are again coincident, that is, the pointer attached to the moving system will move through an angle equal to ϕ. Now, if the current lags or leads with respect to the voltage by an angle ϕ, the fields due to the currents, one set of which is proportional to the main currents, that is, those in fixed coils; the other to the main voltage, that is, currents in moving coils, will also lag or lead by an angle equal to ϕ. The pointer will thus directly indicate the angle of phase difference.

Instruments on this principle may be calibrated to read directly in degrees, but are more frequently calibrated so as to give the power factor of the circuit. This power factor is the average power factor of the system, but the power factor of any one phase is easily obtained by short circuiting the current coils placed in the other phases.

It is easily seen from the theory that these phasemeters can indicate either lag or lead.

Let Fig. 67 represent the condition of a circuit possessing a lag, that is, a circuit in which the minimum value of the current occurs at a later time than that of the voltage. If, however, there were a lead between current and voltage, then at the instant considered, the vector O R would be on the opposite side of O M by an angle ϕ, say, or in other words, the forces F_1, F_3, F_5, F_7, would be reversed in direction, and consequently, also the motion of the coil. By a similar line of argument, it can be shown that the unbalanced load instrument also indicates lag or lead.

Errors in Balanced-Load Instruments.—1. These instruments, as in the case of all air-core instruments, are greatly affected by stray fields, consequently they must be properly shielded.

2. The generation of eddy currents in metal parts should be avoided, as described in air-core ammeters and voltmeters, as a serious error may be introduced from this source.

3. As seen from the theory, the indications of the instrument depend on the maximum value of the current, it will therefore be inaccurate if used on a circuit whose wave form differs from that on which it was calibrated.

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4. An alteration in the frequency will produce a slight error, since it does not affect the fixed and moving systems to the same extent, but for practical purposes this error is so small that it may be neglected.

These instruments are independent of current or voltage since any alteration in either will produce a corresponding effect in both sets of coils.

Errors in Unbalanced-Load Instruments.—These instruments suffer from the same errors as the balanced-load instruments except that 3 is entirely absent, and 4 somewhat smaller. Further, the accuracy is equally independent of variations in current and voltage.

d. PHASEMETER. IRON-CORE.

Construction.—The iron in this instrument usually takes a similar form to that of the carcase of an induction motor built on the following lines. Both the rotor and the stator are fixed, and are made up of thin laminated iron into two cylindrical blocks. The stator only has slots which are given a spiral twist instead of being placed parallel to the main axis of the blocks. This twist is given to overcome the effect of the sudden change in flux-density between the slot and tooth on the coil, the amount of twist being such that the average flux-density acting on the moving coil is the same in any part of the gap. Three fixed coils are necessary, and are wound in the slots of the stator in such a manner that they produce a rotating field. The size of wire used is Nos. 15–17 S.W.G. capable of carrying 5–6 amperes.

The moving coil is made of a rectangular shape and of such a size as to be able to rotate freely in the gap between the rotor and stator. The size of wire and number of turns being approximately the same as would be used in a type A voltmeter. The coil is pivoted between jewels, but does not require any form of control.

This combination of coils most readily lends itself to the measurement of phase displacement on three-phase circuits, where the three fixed coils are put in the three mains and the moving coil put across any one phase. But by suitably wind-

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ing the fixed coils, the instrument could be adapted to either single- or two-phase systems.

Theory.—This is precisely the same as that already given on page 73 for balanced-load instruments, except that in this case the rotating field is produced by the fixed coils instead of by the moving coils, as in the previous case.

Errors.—This instrument will suffer from errors 2, 3, and 4 of balanced-load instruments given on page 75, and is further subject to the slight errors, already discussed, which arise from the presence of iron. But the most serious error for an instrument constructed as described above is that produced when it is used on an unbalanced load if calibrated on a balanced load. The readings on unbalanced loads will lie between $\cos(\phi) \pm \theta \sin \phi$ where θ equals the greatest value of $\frac{\text{load current in one main}}{\text{average load current in all the mains}}$ and ϕ is the angle of lag or lead.

e. Idle Current Wattmeter.

This instrument is used to indicate the imaginary component of a current, which is 90° out of phase with the voltage. The only difference between this wattmeter and the ordinary wattmeter described on page 58 (air) and 65 (iron) is in the connections. For the air-core instrument the moving coil circuit which before was made very non-inductive is now made highly inductive, so that the current flowing in it lags nearly 90° behind the impressed voltage. This is done by putting a choking coil in series with it, and connecting up as before. In the case of an instrument with an iron core, the construction of the parts is the same as for the shunt-coil wattmeter, but instead of connecting the moving coil across the mains through a condenser, it is connected to the terminals of a shunt. In series with a sufficiently high resistance to make it non-inductive.

Theory.—Air-core instruments. In the moving coil, the current, represented by vector O C*mc*, Fig. 68, which is made proportional to the voltage is also made to lag behind the main voltage O V by 90°. Now, if the main current O C is in phase

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with the main voltage O V, then no torque is exerted on the moving coil. But, if the main current lag behind the voltage O V by an angle ϕ, then the component in phase with the voltage O C*mc* equals C sin ϕ, and consequently the torque exerted on the coil will be V C sin ϕ, where V = O C*mc*. C sin ϕ is the wattless component of the current, and, therefore the instrument may be calibrated to read what is often called the wattless watts which is a "non est" except in name.

Iron-Core Instruments.—In this case the main flux O F, Fig. 69, produced by the fixed coil, is proportional to the main voltage O V, and lags 90° behind it. The current O C *m c*, passing through the moving coil, is proportional to and in phase with the main current, since it is taken from the

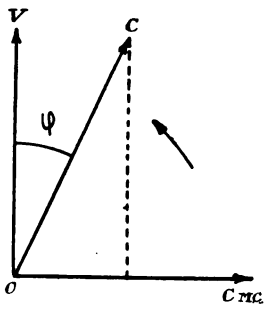

FIG. 68.

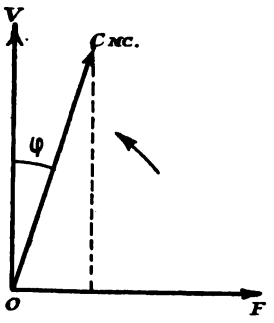

FIG. 69.

terminals of a shunt in the main circuit, and flows through a non-inductive resistance. Now, as before, when the current is in phase with the voltage in the main circuit, no torque is exerted, but if the current lags by an angle ϕ, then O C *m c* will lag by angle ϕ, and the component in phase with the flux O F will equal C sin ϕ.

The torque exerted on the moving coil is, therefore, proportional to V C sin ϕ as before, since O F is proportional to V, the main voltage, and O C *m c* to C, the main current.

The readings of these instruments will be dependent on the frequency. The instruments to give accurate readings must, therefore, be used on a constant frequency system.

Since the construction of this instrument is the same as

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an ordinary wattmeter, it may be calibrated to read the apparent watts as well as the so-called wattless watts, if a small switch be provided to change over the connections. It would then be possible to obtain the power factor of the circuit by dividing the wattless watts by the apparent watts, the result being tan ϕ. Whence from a book of tables cos ϕ can be obtained.

If the voltage of supply is constant, these instruments may be calibrated to read C sin ϕ, i.e. the wattless current.

Errors.—The errors which these instruments are likely to suffer from are the same as those mentioned in the ordinary wattmeters described in the references given above. Self-induction will, of course, not produce an error in this case, as that is what is required, but the error due to frequency will now be large, since the current, flowing in the moving coil in the one and the fixed coil in the other, depends on the impedance, i.e. $\sqrt{R^2 + 4\pi^2 f^2 L^2}$. There may also be errors introduced by the shunt, if one be used, when precautions similar to those mentioned on page 44 must then be taken.

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CHAPTER V.

ELECTRO-DYNAMIC PRINCIPLE.

INDUCTION SYSTEM.

Shifting Field Class.—The instruments belonging to this system are frequently called induction instruments, since they depend for their actuating force on the mutual action between a field, produced by a current proportional to the property to be measured, and another field due to an induced current.

There is more than one way of explaining the action of these instruments, but the method which has been used here is perhaps the simplest and the one that is most easily applicable to this class. The idea conveyed by the term "shifting field" will be better understood by a perusal of the theory, so that no definition need be given at this point. There are many different devices used for producing this effect, but of those employed in indicating instruments, only two will be given. The description of several other such devices may be found in any modern book dealing with induction watt-hour meters.

These instruments cannot, of course, be used on continuous current circuits, as their action depends entirely on the property of induction possessed by an alternating current.

a, b. AMMETERS AND VOLTMETERS.

Construction.—The moving system of these instruments, Fig. 70, consists of a light aluminium or copper disc D, generally of a circular shape, fixed to a spindle which carries the pointer and balance weights. This spindle is carefully pivoted between jewels in a manner similar to that described on

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page 40. The instruments are spring controlled, one end of the spring being securely fixed to the spindle by means of a small collet, whilst the other is attached to the frame in which the spindle is pivoted. No connections to the moving disc are needed, so that it is not necessary to insulate the springs. The disc is so placed that its rim revolves in the centre of the gap of an electromagnet E M, which is made up of soft sheet-iron laminations in a rectangular shape. The section used is from 0·5 to 1 square inch. The pole faces of this magnet

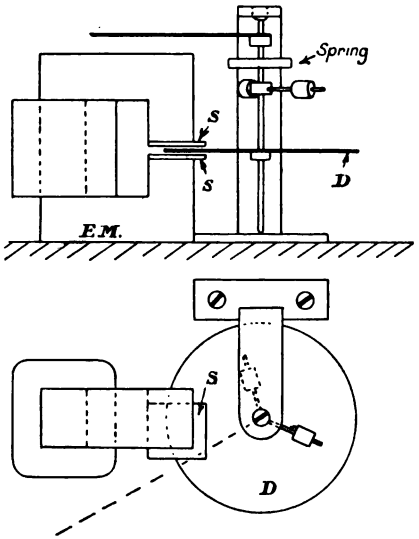

FIG. 70.

are partially shielded to the extent of about 80 per cent. of the whole, by screens S of copper or aluminium. The screens are usually a little thicker than the disc, and are bent up round the edges of the poles or allowed to project about 0·125 to 0·1875 inch, so as to prevent the field cutting the disc on any but the side not shielded.

The winding used for the magnetising coil for ammeters has from 300 to 400 ampere turns. The size of wire used depends on the current to be carried by the coil, but for large currents it becomes necessary to employ current transformers.

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For voltmeters the size of wire is about Nos. 30–36 S.W.G., the number of ampere turns being approximately the same as for ammeters. If the instruments are to be used on high tension mains, a voltage transformer is employed, designed to give a secondary voltage of about 100 volts. As they stand, these instruments are fairly dead-beat, but as a rule, a further damping force is added, which takes the form of a small permanent magnet acting on the disc. The small magnet should be efficiently shielded to protect it from demagnetisation due to the alternating field of the magnetising coil.

Connections.—For ammeters the magnetising coil is connected to the two terminals of the instrument which are then put into one main, or which may be connected to the secondary of a current transformer.

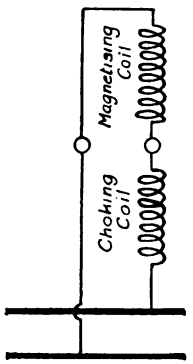

FIG. 71.

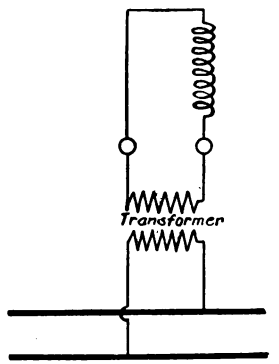

FIG. 72.

In the case of the voltmeter, the coil is connected as before to the terminals of the instrument which are put across the mains in series with a choking coil, for voltages between 500 and 1000 volts, see Fig. 71, but when used on a high potential system, the terminals are connected to the secondary of a voltage transformer, see Fig. 72.

Theory.—The current in the magnetising coil causes a flux to pass across the gap which consequently must cut the shield and disc. The currents induced in these will, according to Lenz's law, oppose the action which produces them, that is,

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they will produce fields which act in opposition to the main one. Further, since the induced electromotive forces are proportional to the rate of change of flux, then the induced fluxes will lag 90° behind the main one, if the disc and screen themselves introduce no lag.

Now let us consider the changes in the fields for a complete cycle of the magnetising current. Suppose at any instant the main current is zero, and the induced flux is a maximum. If now the magnetising current increases so as to produce a N pole, then the polarity of the flux due to the current induced in the shield is S, and is decreasing in magnitude. When the main flux reaches its maximum, then the induced flux is zero, and as the main flux decreases to zero, the induced flux will increase to its maximum, and be of the same polarity as the main, i.e. N. Next, the main flux

TABLE 6.

Angle. °	Main Flux is	Induced Flux is	Polarity of	
			Main Flux is	Induced Flux is
0	0	+ maximum	..	S
0–90	increasing +	decreasing +	N	S
90	+ maximum	0	N	..
90–180	decreasing +	increasing −	N	N
180	0	−maximum	..	N
180–270	increasing −	decreasing −	S	N
270	− maximum	0	S	..
270–360	decreasing −	increasing +	S	S

commences to increase, but is of opposite polarity S, at the same time, however, the induced flux decreases, but still remains of the same polarity as before, that is N. Now, when the main flux decreases, its polarity remaining S, the induced flux increases, its polarity also being S. These changes have been put into Table 6 given above, and show how the field shifts across the pole face from the unshaded to the shaded part.

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Since there are currents induced in the disc by the main field, there will be a force between them and this shifting field. This force, which will cause the disc to move in the same direction as the field, is proportioned to the product of the magnitude of the induced disc-currents and the magnitude of the shifting field, that is

$$\text{force} \propto C_1 F$$

but C_1 is directly proportional to the rate of change of F, and inversely proportional to the resistance of the disc, that is

$$C_1 \propto Ff \div R \qquad \text{where } f = \text{frequency}, \; R = \text{resistance of disc}$$

$$\therefore \quad \text{force} \propto F^2 f \div R$$

Now F is the flux produced by the magnetising current C, therefore force $\propto C^2 f \div R$, and since the instruments are spring controlled, the pull of the spring being proportional to D, the deflection in degrees, it follows that

$$D \propto C^2 f \div R$$

If this current (C) is made proportional to either the current or voltage in the main circuit, then the instrument can be calibrated as an ammeter or voltmeter, as the case may be.

This theory could have been obtained by the same reasoning as will be employed in connection with the wattmeter of this class. But by presenting it in the simple manner given, it is thought that it will enable the more complex theory to be easily understood.

Errors.—The main sources of error met with in these instruments are due to :—

1. Temperature changes.
2. Variation in frequency.
3. Eddy currents in the iron.
4. Varying permeability of the iron.
5. Hysteresis in the iron.
6. Stray magnetic fields.

1. If the temperature of the instrument changes, then the resistance R of the disc will alter, the result being that for the

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same flux the magnitude of the induced current will be less or more as the case may be, and, consequently, the torque will be smaller or larger than it should be. There are several methods in which this difficulty may be overcome.

(*a*) By shunting the magnetising coil with a non-inductive resistance wound with such a gauge of wire that its resistance increases at exactly the same rate as that of the disc. Since the resistance of this additional coil varies with change of temperature, the current carried by it will also vary, the result being that more or less current will flow through the main coil as the resistance of the shunt coil increases or decreases. More current in the main coil means a larger flux through the disc, and consequently an increased torque, in this way, the error due to change in temperature can be exactly compensated.

(*b*) In the second method, a short-circuited coil is placed round one pole of the magnet. This coil will neutralise a certain amount of the main flux, depending on the magnitude of the current flowing in it, which in turn is governed by the resistance of the coil. With increased temperature, less current will flow in the short-circuited coil, and, therefore, less of the main field will be neutralised. This allows a larger flux to cut the disc, and in this way to compensate for the increased resistance of the disc.

(*c*) In series with the magnetising coil is placed a choking coil which has a gap in its magnetic circuit. In this gap is placed a small piece of iron supported by a composite strip, which is made to bend by variations in temperature, thus drawing the iron in and out of the gap, and so varying the self-induction of the instrument. By suitably arranging the parts, any variation in the torque of the instrument will be balanced by a corresponding variation in its reactance.

2. The eddy voltages induced in the disc depend on the number of lines cut per second, which is obviously proportional to the frequency (see Theory). It follows, therefore, if the instrument be practically non-inductive, that the reading would increase for every increase in frequency. On the other hand, if the instrument is highly inductive, the choking effect of the

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coil will produce a greater change in the torque than will an increase in the eddy voltages with the result that the readings will fall. By suitably adjusting the resistance and reactance of the circuit, it is possible to compensate the instrument for a variation in frequency of from 10–20 per cent.

This might be done when correcting for temperature changes; only one coil need then be used.

3. With regard to eddy currents, the effects of these may be made negligible by carefully laminating the iron. As a rule ordinary transformer laminations are used, the average thickness being 15 mils.

4. This error is similar to that already spoken of under No. 7, page 56, but will be largely discounted by the presence of the air gap. In these instruments, the ratio of the length of the air gap to the length of the iron path is about $\frac{1}{40}$, so that for practical purposes this error may be neglected.

5. This error can never be really eliminated, but it may be greatly reduced by using an iron possessing a low value for its hysteresis loss.

6. Stray alternating fields will produce eddy currents in the disc, and will thus cause an alteration in torque. This error may amount to 0·5 per cent. of maximum scale reading, unless the movements are efficiently shielded by iron cases.

Errors Nos. 3 and 4 affect the magnitude of the working flux, and No. 5 produces a phase displacement between the flux and the current producing it.

In ammeters and voltmeters these errors (i.e. Nos. 3, 4, and 5) cannot, strictly speaking, be called errors. Since, provided they remain constant for any definite current, they will be the same under working conditions as when the instrument was calibrated, and may therefore be looked upon as simply altering the calibration.

Under working conditions, it is found that there is practically no error introduced by wave form. The curve given, Fig. 73, was derived by plotting the number of amperes obtained from a standard against those given by the instrument when the main current had different wave forms. Three wave

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forms were used, first a sine wave, second a flat topped, and third a peaky topped. The constant $\frac{\text{maximum value}}{\text{effective value}}$ had values for the three waves as follows:—

(1) 1·41; (2) 1·2; (3) 1·76. It was found that all the points lay on the straight line shown.

Advantages.—1. This instrument is, if well compensated, one of the most accurate alternate current commercial instruments in use. As a rule, however, exact compensation is difficult to obtain, and for very accurate work it is advisable to use instruments of either type B_1 or D.

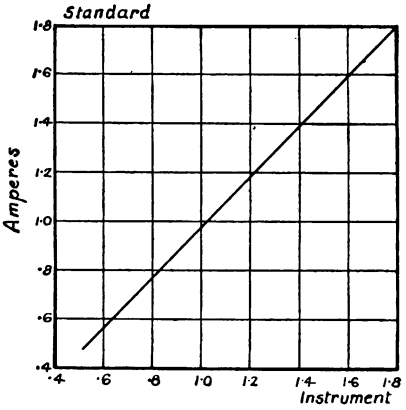

FIG. 73.

2. They possess a very good scale, see Fig. 19, whose divisions are not exactly equal, being slightly compressed at the bottom, but they can be made to very nearly meet this desirable requirement.

3. From the nature of the movement a very large angle of swing, amounting to about 300°, is possessed by these instruments. If this large swing is fully utilised, then the divisions are very open, with the result that readings are easily taken with a very fair amount of accuracy. There are, however, certain drawbacks to a long scale which have already been mentioned.

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c. WATTMETERS.

In these instruments the poles used are sometimes shaded, sometimes unshaded. In the previous section the instrument described was of the first kind, so that here we will confine ourselves entirely to the consideration of the second kind.

Construction.—The construction is similar to that of the ammeter and voltmeter of this class, but in a single-phase instrument two magnets at least are required, and for two- and three-phase instruments more in proportion to the number of phases. The electromagnets are wound one with a winding suitable for an ammeter, the other with a winding suitable for a voltmeter, and are placed near to one another, both, of course, embracing the rim of the disc.

The windings are connected to the circuit exactly as in the case of the ammeter and voltmeter.

The same remarks as to power measurement, as have been made with regard to the type B_1 instrument when connected to polyphase circuits, also apply here.

Theory.—It is easily seen from what has already been said on page 83 that, if the poles are arranged as shown in Fig. 74, a shifting field will be the result, and further, that the cyclic changes will be the same as those given in Table 6, in which the column called "induced flux" is now to be called "shunt flux." It follows, therefore, that the disc will revolve in the same direction as before, that is from shunt to main. Further, the torque will again be proportional to the product of the magnitude of the shifting flux and the magnitude of the induced currents in the disc. In order to deduce the fact that the torque is proportional to the power of the main circuit, let us consider the state of affairs at any instant when the power factor is unity.

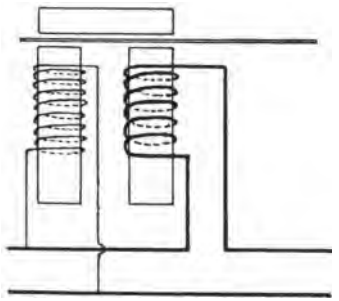

FIG. 74.

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In Fig. 75, let O E be the voltage vector, and let it, at the instant considered, have described an angle pt from its original position. Now, since the shunt magnet consists of many turns of fine wire wound on an iron core, the self-induction will be sufficient to make the current flowing in it practically 90° out of phase with the voltage E producing it. By means of any of the compensating devices used in practice the flux $O S_1$ produced by this current can be made to lag exactly 90° behind O E. The eddy electromotive force induced in the disc by the shunt flux will be $O S_D$ lagging 90° behind $O S_1$, and if the disc has no self-induction, then the eddy flux due to the shunt coil may be represented by $O D_2$ in magnitude and direction.

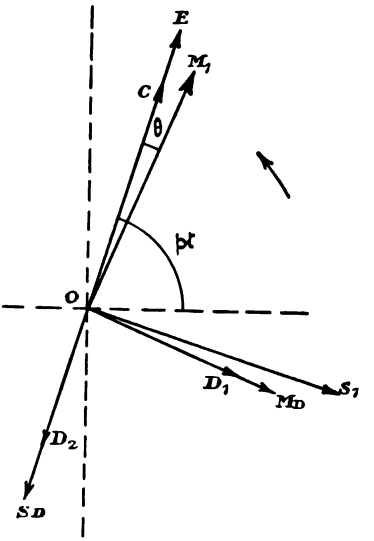

FIG. 75.

Since the power factor is unity, the main current vector O C coincides with the main voltage vector O E, but the flux produced by the main current will lag by a small angle θ, owing to hysteresis in the iron. Therefore, we may represent the main flux vector by $O M_1$. The eddy electromotive forces induced in the disc by this flux will lag 90° behind it, and may be represented by $O M_D$, consequently $O D_1$ will represent the eddy flux due to the main flux.

The torque of this instrument depends on the electrodynamic action of the fluxes present in it, of which there are four, viz.: $O M_1$, $O S_1$, $O D_1$, and $O D_2$. It is clear from Fig. 75 that no effective torque can be exerted between $O M_1$ and $O D_1$, or $O S_1$ and $O D_2$, since they are respectively perpendicular to one another. As a result, the only torques which need to be considered here are those exerted between $O M_1$ and $O D_2$, and $O S_1$ and $O D_1$.

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The torque exerted between $O M_1$ and $O D_2$ is equal to the product of the instantaneous value of these functions, that is

$$T_1 = \{O M_1 \sin (p t - \theta)\} \{- O D_2 \cos (90 - p t)\} C_0 \quad (1)$$

similarly torque between $O S_1$ and $O D_1$ is

$$T_2 = \{- O S_1 \cos p t\} \{- O D_1 \cos (p t - \theta)\} C_0 \quad (2)$$

Where C_0 is a constant depending on the construction of the instrument.

From the construction of the instrument it is seen that these torques are acting on the disc in opposite directions, therefore the total torque is

$$T = T_1 - T_2 = \{-O M_1 O D_2 \sin (p t - \theta) . \cos (90 - p t)\} C_0 - \{O S_1 O D_1 \cos p t . \cos (p t - \theta)\} C_0 \quad . \quad (3)$$

Now it follows that the ratio of the main eddy flux to the main flux will be the same as the ratio of the shunt eddy flux to the shunt flux, and will be dependent on the frequency of the system and the resistance of the disc.

$$\therefore \quad \frac{O D_1}{O M_1} = C_1$$

and

$$\frac{O D_2}{O S_1} = C_1$$

that is

$$O D_1 = O M_1 . C_1$$

and

$$O D_2 = O S_1 . C_1$$

Substituting these values for $O D_1$ and $O D_2$ in equation 3, we obtain

$$T = - C_0 C_1 O M_1 O S_1 \{\cos p t . \cos (p t - \theta) + \sin p t . \sin (p t - \theta)\}$$
$$= - C_0 C_1 O M_1 O S_1 \cos \theta.$$

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Now C_1 and C_0 are constants, and O M_1 and O S_1 represent the main current C and main voltage V respectively, therefore

$$T = - C V \cos \theta \text{ . const.}$$

Suppose now that the current lags by an angle ϕ behind the voltage in the main circuit, then it is easily seen from the vector diagram that the angle θ will become $(\theta + \phi)$, therefore

$$T = - C V \cos (\theta + \phi) \text{ . const.}$$

If θ be so small as to be negligible, then

$$T = - C V \cos \phi \text{ const.}$$

The negative sign simply shows the direction of the torque, and since the instruments are spring controlled

$$D \propto C V \cos \phi.$$

Errors.—As has been shown on page 62, the total error may be represented as the fraction

$$\frac{\text{Reading of instrument in watts} - \text{true watts}}{\text{true watts}}$$

which in this case

$$= \frac{C V \cos (\phi + \theta) - C V \cos \phi}{C V \text{ . } \cos \phi}$$
$$= - \tan \phi \text{ . } \theta$$

In this instrument θ can never be reduced to such a small quantity as it can be in type B_1 wattmeters.

The errors which occur in shifting field wattmeters are as outlined under the ammeter and voltmeter of this class.

No. 1 is the same as before and must be compensated in a similar manner.

No. 2. In the theory the torque is shown to be

$$= - C_0 C_1 \text{ O } M_1 \text{ O } S_1 \cos \theta.$$

Now O M_1, which represents the main current, is practically

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independent of f, the frequency, since the coefficient of self-induction in that circuit is small. But $O S_1$, which represents the current proportional to the main voltage, is proportional to $\frac{I}{f}$, since there is an angle of lag equal to 90° in this circuit.

Also, $C_1 = \frac{f}{R}$ where R = resistance of disc.

By substitution in the above formula it is found that

$$T = - C_0 \frac{f}{R} C \frac{V}{f} \cos \theta$$

$$= - \frac{C_0}{R} C V \cos \theta = - C V \cos \theta \text{ . const.}$$

It is thus seen that the readings given by this instrument are practically independent of variations in frequency.

Nos. 3, 4, and 5 now become errors, since the current to be measured is rarely the same as that with which the instrument was calibrated.

As a result of these various errors, these instruments can only be looked upon as accurate when used upon a unity power factor system.

As to advantages, these wattmeters correspond very closely with the ammeter and voltmeter.

d. Idle Current Wattmeters.

Construction.—Since instruments of this class only work when the currents producing the shifting field are 90° out of phase, a simple method of measuring the wattless component of the power is at once evident. For if a wattmeter movement similar to that just described, see page 88, and with the voltage coil so wound and connected that the current in it is in phase with the current in the main coil, then as the theory will show, the reading given by the instrument will indicate the so-called wattless watts. Beyond the method of winding the shunt coil, there is no difference between the construction of this instrument and that of the ordinary wattmeter.

Theory.—The vectors used in Fig. 76 have the same signi-

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ficance as in the previous section. In this instrument, however, the shunt flux $O S_1$ will, for unity power factor, coincide with the voltage vector $O E$, $O D_2$ the eddy shunt flux will of course be 90° behind this. The total torque is now

$$\begin{aligned} T &= C_0 \{ - O S_1 \, O D_1 \cos (90 - pt) \, . \, \sin (90 - pt + \theta) \\ &\quad + O M_1 \, O D_2 \cos (90 - pt + \theta) \, . \, \sin (90 - pt)\} \\ &= C_0 C_1 \, O S_1 \, O M_1 \{ - \cos (90 - pt) \, . \, \sin (90 - pt + \theta) \\ &\quad + \cos (90 - pt + \theta) \, . \, \sin (90 - pt)\} \\ &= - C_0 C_1 \, O S_1 \, O M_1 \sin \theta \quad . \quad . \quad . \quad . \quad (1) \end{aligned}$$

If the main current lags by an angle ϕ behind the voltage, then the angle θ becomes $\theta + \phi$.

$$\therefore \; T = - C_0 C_1 \, O S_1 \, O M_1 . \sin (\theta + \phi)$$

Now, if θ is made very small, so as to be negligible, then equation 1 is zero, that is to say, the instrument does not indicate if there is no lag in the main circuit. But when a lag occurs to the extent of ϕ say, then

$$T = - C_0 C_1 \, O S_1 \, O M_1 \sin \phi$$

and this is equal to

$$T = - V C \sin \phi \text{ const.}$$

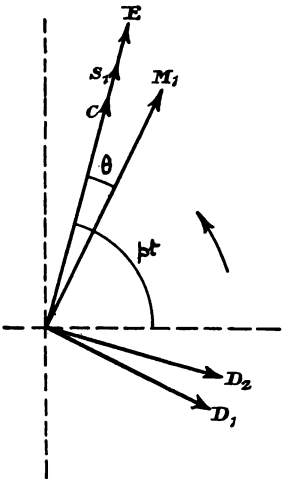

FIG. 76.

Now C sin ϕ is the wattless component of the current, thus the instrument will give a reading proportional to the wattless watts.

If V be made constant, then the instrument will give readings proportional to the wattless current in the circuit.

Errors.—The errors which occur in this instrument must be the same as those in the ordinary wattmeter of this system with the exception of No. 2, since the construction of the two movements is similar, and therefore what has been said respecting the latter with regard to their elimination will equally apply to this.

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With regard to error No. 2, it will readily be seen that the readings of this instrument must be greatly affected by frequency. The current in the shunt coil is now in phase with the main current, and consequently will be nearly independent of the frequency provided the self-induction is comparatively low. Thus the torque becomes

$$= - C_0 \frac{f}{R} C V \cos \theta \text{ approximately.}$$

There is no doubt, but that this error might be partially reduced by the application of the method outlined under the ammeter and voltmeter, see page 85, but this adjustment would be difficult to perform accurately.

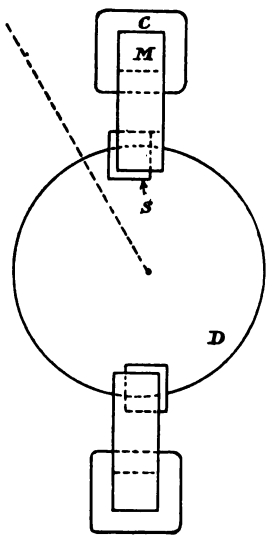

FIG. 77.

e. FREQUENCY METER.

Construction.—This instrument differs slightly from those already described in that it possesses two laminated electromagnets M, situated as shown in Figs. 77 and 78, acting on an aluminium disc D, eccentrically pivoted, or of irregular shape, which is capable of rotating in the gaps of the magnets just mentioned. The magnetising coils C are wound in opposite directions with an equal number of turns of wire of the same gauge as that used for type B_2 voltmeter. One of the poles of each magnet has a screen S similar to that described on page 81. The disc is fixed to a spindle which also carries the pointer and balance weights, and the whole is very carefully balanced so as to be capable of remaining in any position which the forces cause it to take up. The spindle is pivoted between jewel centres, and no form of control is needed. The magnetising coils are connected on lines similar to that

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described on page 69 for the moving coil of the single-phase power factor indicator. One end of each coil is joined together, and the common junction brought to a terminal of the instrument. The other two ends are respectively connected to the

FIG. 78.

other two terminals. When the instrument is connected to the circuit, the terminal to which the common junction is joined is directly connected to one main. The other two terminals are brought to a resistance box having two branches (see Fig. 79). The common junction of the branches in its turn is connected to the other main.

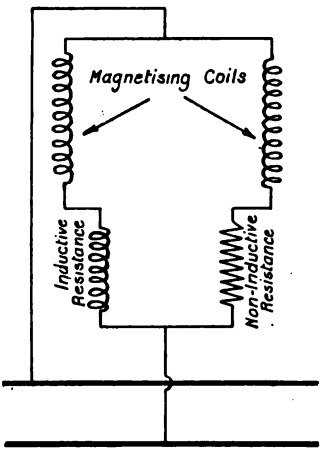

FIG. 79.

Theory.—Since one of the magnetising coils has an inductive resistance, and the other has a non-inductive resistance in series with it, it follows that the one circuit has a much greater impedance than the other. When a current of definite frequency flows through the instrument circuit, certain currents will flow through the coils, the amount in the one case depending on the impedance and in the other on the resistance of the coil. Now since the magnets are wound oppositely, the torques will oppose one another, and when equal will balance. If the frequency of the main circuit change, the impedance of the inductive circuit will be altered, and as a result, the torque exerted by this magnet will also

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be altered, while the torque exerted by the other magnet remains constant. Now this alteration in torque will cause the disc to rotate, but since the disc is irregularly shaped, the rotation will reduce the torque due to one magnet and increase that due to the other magnet, and thus obtain a balance in which the disc will remain at rest. Hence the instrument may be calibrated to read frequency. Fig. 80 will give some idea of what the scale of this instrument is like. It will be noticed that it is comparatively short, but that the divisions are nearly equal.

FIG. 80.

Errors.—With the exception of No. 2 (frequency) the errors of this instrument will be practically the same as given on page 84 for the ammeter and voltmeter of this class.

There is no outstanding advantage which can be claimed for this instrument, and as far as the accuracy of the readings and the ease with which a reading can be made is concerned, it is not so good as the vibrating reed form described in Chapter X.

f. LEAKAGE INDICATOR.

Instruments of this class could be constructed to measure the insulation of a system in a somewhat similar manner to that done in type C instruments, but up to the present, they have not been developed to any great extent. Probably, this is due to the greater cost of such instruments over the type C class.

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CHAPTER VI.

ELECTRO-DYNAMIC PRINCIPLE. INDUCTION SYSTEM.

ROTATING FIELD CLASS.

THE foundation for the manufacture of these instruments was laid by Professor G. Ferraris in 1885, when he discovered the method of producing a rotating field by the superposition of two alternating fields. The original idea was to use this fact as the basis for an alternate current motor, but when experiments were conducted with the motor they designed, it was found unsuitable for their purpose. It was then suggested by the Professor that the small motors which could be built on this principle might be used in the construction of electricity meters. This was done, and they were found to answer very well. The switchboard instruments about to be considered are a modification of these electricity meters.

a, *b*. AMMETERS AND VOLTMETERS.

Construction.—For a rotating field to be produced, it is clear that two or more sets of coils must be used, and that the currents flowing in them have a phase relation to one another such as conforms to the theorem given on page 73.

In these instruments, two sets of poles are used which are each wound with about the same number of ampere turns, so as to produce approximately equal fluxes. The one set A, Fig. 81, is made practically non-inductive, so that the current in B is nearly 90° out of phase with that in A.

In the centre of the instrument is placed a circular block of stampings, the size being such as to leave a narrow gap

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between the pole faces and themselves. A hollow aluminium or copper drum D is pivoted in the usual way between jewels, so as to move evenly in this gap. The spindle which carries the drum also has attached to it the pointer, balance weights and spring. This movement is practically dead-beat, but an additional damping force which is sometimes added usually takes the form of a horse-shoe magnet (which must of course be shielded), acting on the drum.

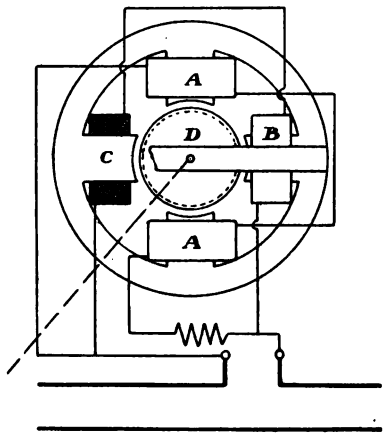

FIG. 81.

For ammeters, the resistance of the instrument must be kept low in order to avoid a large power consumption. This end is realised by putting a low resistance in series with one set of coils which, combined with the self-induction possessed by the other set, is found sufficient to produce a satisfactory rotating field.

On the other hand, the resistance of a voltmeter must be high. This is obtained by winding the coils with a much smaller gauge of wire than that used for ammeters, which had to be of sufficient section to carry the current to be measured. In series with one set of coils is placed a high non-inductive resistance, and in series with the other a choker, the two sets being connected in parallel to the terminals of the instrument.

Ammeters of this class can be used on circuits carrying

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currents up to 300 amperes if connected as given below, but for ranges above this transformers have to be used. Ordinary voltmeters, however, cannot be used on circuits above 500 volts unless connected with a voltage transformer.

Connections.—For single-phase circuits, the ammeter is directly connected in one of the mains (see Fig. 81). In the case of two- and three-phase systems, two and three instruments respectively must be used if the current in each phase is required to be known, unless the system is a balanced one, in which case the current in each phase is equal.

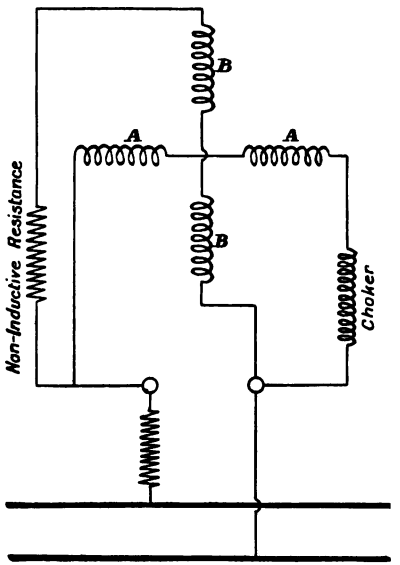

FIG. 82.

The voltmeter is always connected across the mains in series with a resistance if needed (see Fig. 82), and may be provided with a switch so as to read the voltages across the other mains, if used on a polyphase system.

Theory.—It is seen from the configuration of the parts in this instrument that the resultant field produced due to the superposition of the different fluxes will be a rotating field and not a shifting one. The centre about which the field rotates

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is the centre of the drum, so that the field is always cutting the surface of the drum at right angles. Now, since in this instrument there are only two main fluxes, one due to A coils, the other due to B coils, the same theory as has been given for wattmeters, class 1 of this system, will also hold good here with the following modifications.

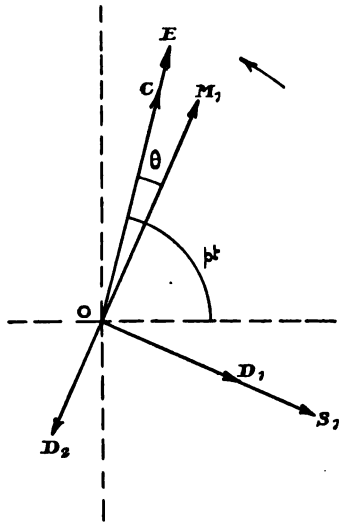

FIG. 83.

In Fig. 83, let O E, O C, θ, pt, C_0 and C_1 have the same meaning as before, and let

$$O M_1 = \text{flux due to A coils}$$
$$O S_1 = \text{flux due to B coils}$$

which, in this case, is 90°, or, nearly so behind $O M_1$

$$O D_1 = \text{eddy flux in drum due to flux } O M_1$$
$$O D_2 = \text{eddy flux in drum due to flux } O S_1$$

Then, as before

$$T_1 = O M_1 \, O D_2 = \{O M_1 \sin (pt - \theta)\} \{ - O D_2 \sin (pt - \theta)\} C_0$$

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and

$$T_2 = O S_1 \, O D_1 = \{ - O S_1 \sin (90 - pt + \theta)\} \{ - OD_1 \sin (90 - pt + \theta)\} C_0$$

$\therefore$

$$T = T_1 - T_2 = C_0 \{ - O M_1 \, O D_2 \sin^2 (pt - \theta)\} - C_0 \{O S_1 \, O D_1 \cos^2 (pt - \theta)\}$$

$$= - C_0 C_1 \, O M_1 \, O S_1 \{\sin^2 (pt - \theta) + \cos^2 (pt - \theta)\}$$

$$= - C_0 C_1 \, O M_1 \, O S_1$$

Now, in ammeters $O M_1$ and $O S_1$ are both proportional to C, the main current, therefore

$$T = - C^2 \text{ const.}$$

since both C_0 and C_1 are constants.

If the instrument is a voltmeter, then

$$T = - V^2 \text{ const.}$$

The negative sign as before simply shows the direction of the torque, and since the controlling force of the instrument is that of a spring, therefore

$$D \propto C^2 \text{ or } V^2$$

Errors.—From the similarity between this and the shifting field instrument, it follows that the errors of this will be much

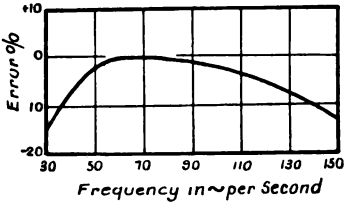

FIG. 84.

the same as those of that instrument given on page 84, and must be corrected in a similar manner.

Figs. 84 and 85 show the error in a voltmeter and ammeter

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respectively, due to variations in frequency. The small curve in Fig. 85 gives this error as found in one of the latest ammeters made by the American Westinghouse Co., and gives

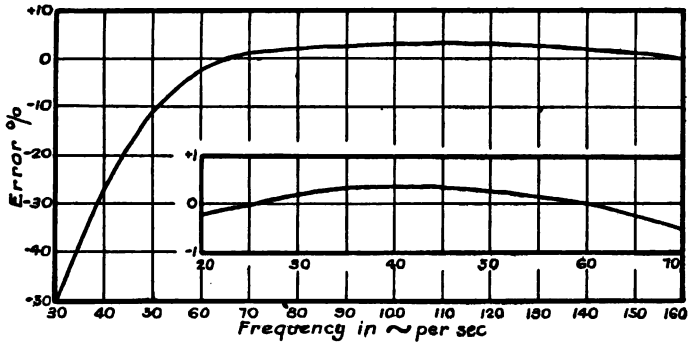

FIG. 85.

an idea of how excellently compensated these instruments can now be obtained.

Advantages.—These are practically the same as in the former class. There is, however, not so large a swing of pointer, and, consequently not so long a scale, but by a slight modification in the construction this could easily be obtained.

c. WATTMETERS.

Construction.—The construction of this instrument is practically the same as that already described for an ammeter or voltmeter, but the connections have to be altered.

One set of coils is wound similarly to those required for a voltmeter, that is, with a large number of turns of small gauge wire; the other set is wound with a wire of section capable of carrying the main current. These instruments require four terminals, to two of which the current coils are connected, and to the remaining two the voltage coils. In order that the current flowing in the latter may be made to lag exactly 90° behind the voltage, a very neat device is commonly employed with these wattmeters. A Wheatstone's bridge P Q R S is made up of two arms P Q and S R, containing self-induction

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and two Q R and P S possessing only resistance. Any two opposite corners of this bridge P and R are connected across the mains, as shown in Fig. 86, the other two corners Q and S are connected to the voltage terminals of the instrument. By suitably adjusting the four arms, it is possible to obtain exactly 90° difference of phase between the voltage of the

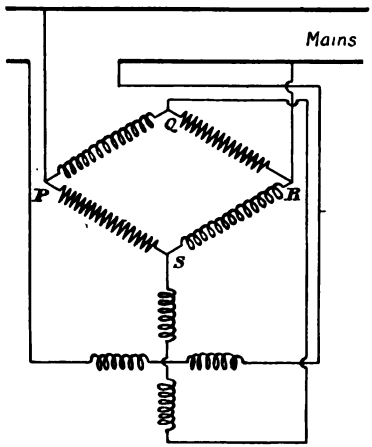

FIG. 86.

mains and the voltage across the instrument coils. This arrangement prevents any small error which might otherwise arise due to the phase difference not being exactly 90°.

Connections.—The current coils are put in one main, and the voltage coils across one phase for a single- and two- or three-phase balanced systems. For two- and three-phase unbalanced circuits, two wattmeters have to be used, and these are usually combined in one case, as has been described for the type B_1 wattmeters.

Similar remarks to those on page 58, with reference to power measurement, also hold good in regard to these instruments.

Theory and Errors.—These are identical with those for the wattmeters of class 1, and need not, therefore, be again considered here.

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The divisions of the scale of this instrument can be made very nearly equal, as is well seen from Fig. 87, which is a

FIG. 87.

photo of a Ferraris wattmeter as made by Messrs. Siemens Bros.

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CHAPTER VII.

ELECTRO-MAGNETIC PRINCIPLE.

MOVING IRON SYSTEM.

FOR private installations where a small switchboard is necessary, this type of instrument is the one most frequently used, because it can be made sufficiently accurate for all practical purposes at a very small cost. It can be given a finish in all respects as good as that given to type A or B, and is now being very largely used in connection with small motors.

a, b. AMMETERS AND VOLTMETERS.

Construction.—All of the instruments on this principle consist of a piece of iron which is pivoted, so that it can move from the weaker into the stronger part of a field, which field is produced in some form of solenoid.

There are usually between 400–600 ampere-turns on the solenoid, which generally consists of a bobbin (wound with the requisite number of turns), and made preferably of insulating material, but it may be of metal if care is taken to prevent the generation of eddy currents in it.

For ammeters, the size of wire or strip will vary as the range of the instrument, since the whole of the current to be measured has to pass through the solenoid. In the case of high range instruments, from 400 amperes and upwards, the coils may be made of cast copper, no bobbin then being necessary. This is an excellent design, since it gives a large surface for radiation.

In ammeters, the number of turns needed will, of course, vary inversely as the current to be measured. In the case of voltmeters, a current of 0·05 ampere is used, and consequently

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about 5000 turns are required, the gauge of wire being 36 to 40 S.W.G. When this coil is fixed in an iron pot, the principal axis is usually placed horizontal, and parallel to the base of the pot, so that very little of the return path of the lines may lie in the iron case, since the magnetisation of the pot would introduce an error. If the coil has been fixed with its principal axis at right angles to the base, it should be magnetically insulated from it, and at least 0·5 inch left between the bottom of the coil and the base of the pot; or the pot might be cut away in the neighbourhood of the bottom of the coil, and an insulator substituted, if some form of magnetic

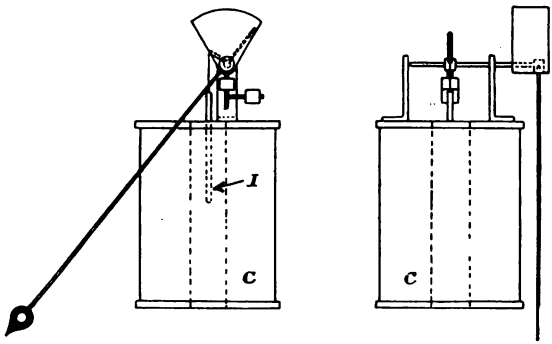

FIG. 88.

shield has been provided outside this insulator. There is a further advantage in having the axis of the coil parallel to the base, in that when fixed on a switchboard where the bus-bars are placed immediately behind, the effect of currents flowing in these bus-bars will be nil, whereas if fixed perpendicular to the base, the effect will be a maximum.

The movement, Fig. 88, consists of a piece of soft iron I, which is attracted into the core of the coil C. This moving iron is attached, either directly or by means of a light arm, to the spindle, so as to convert the pull of attraction into a torque.

The control employed most frequently is that of gravity No. 4, page 23, but a spring control is sometimes used when the instrument is fixed to an unsteady switchboard, as on a

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motor car or ship. The commonest form of damping employed is No. *2a*, page 24. The pot, pointer, balance weights, scale, opening, and method of pivoting, are practically the same as for type A ammeter and voltmeter, page 41.

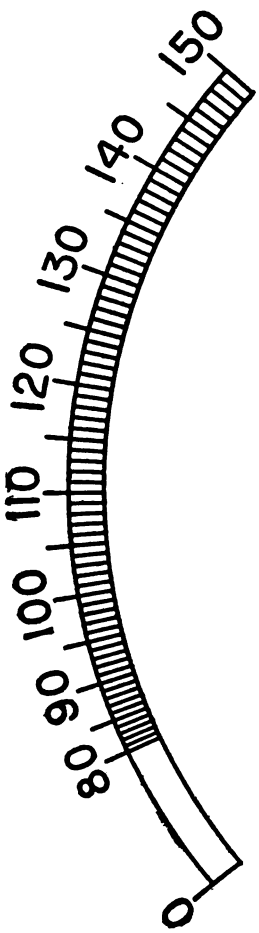

FIG. 89.

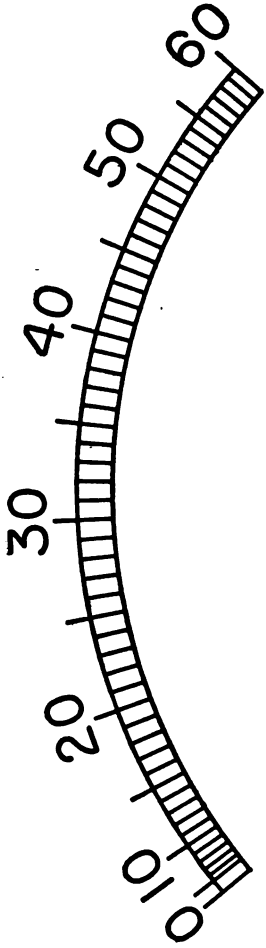

FIG. 90.

The great aim of the manufacturer in designing instruments of this system, is to make them cheap and reliable. Since they are cheap, they will have to do duty under all sorts of

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conditions, and it is essential, therefore, that the pot be hermetically sealed, so that dampness may not rust the moving iron. To further guard against rust, the iron is frequently plated with nickel, copper, or zinc. Besides, as they will be often under the control of people who know very little about electricity, they must, therefore, be made exceptionally strong, and further the solenoid should be capable of standing an overload of 50 per cent. for some time without seriously affecting the accuracy of the instrument.

Theory.—The moving iron is attracted into such a position by the field of the coil, that the magnetic reluctance of the circuit is reduced to a minimum, that is, it depends on the pull which the coil exerts, and this is proportional to the square of the flux density, consequently, this instrument will approximately follow a square law.

The effect produced by this movement on the equality of the scale divisions is very well shown in Figs. 89 and 90, which are the scales obtained from a voltmeter and ammeter respectively.

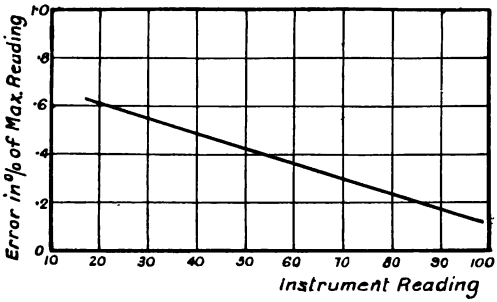

FIG. 91.

Errors.—The only errors likely to seriously affect these instruments are caused by:—

1. Stray magnetic fields.
2. Hysteresis.
3. Change of wave form.
4. Change of frequency.

1. Instruments that possess a strong field of their own are less likely to be affected by strong external fields than those

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which have only a weak field, but to protect such instruments it is usual to put the movement in a cast-iron pot. This effectually protects them from stray fields, but in its turn produces error, unless care is taken to arrange the coil as described in the construction, page 106. Fig. 91 gives the error found in an ammeter at different loads, due to a bus-bar carrying a current of 1000 amps. at a distance of one meter.

2 and 3.—It is found that with this type of instrument the readings taken when going up the scale are less than those taken when coming down for the same reading on the

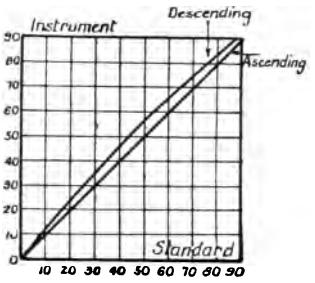

FIG. 92.

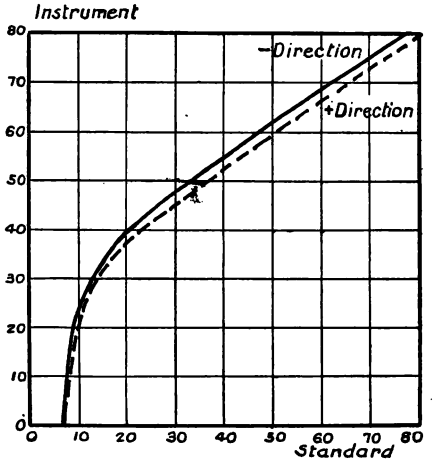

FIG. 93.

standard, as shown in Fig. 92. This error is due to hysteresis in the soft iron movement. Fig. 93 shows the error produced by hysteresis in a somewhat different manner from Fig. 92.

Here the readings of the instrument due to the current flowing in the positive direction are plotted against those of the standard. The current is now reversed and a second set of readings taken, these being plotted as before. The difference between the curves shows the error due to hysteresis. Since hysteresis is the lagging of the magnetic condition behind the magnetising force, it follows that in order to reduce this error, either a very low or else a very high flux

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density must be used. This can be seen from B and H curve, Fig. 94, which shows that the increase in B is small for small increases of H, at low values of H, and again at very high values. In this figure the values of H have not been pushed as far as to approach saturation. When this is done the curve will have a similar shape to that shown in Fig. 23. It follows that for these two stages of the magnetisation of the iron, the lagging caused by hysteresis will be practically negligible, and of the two the first is the preferable, because

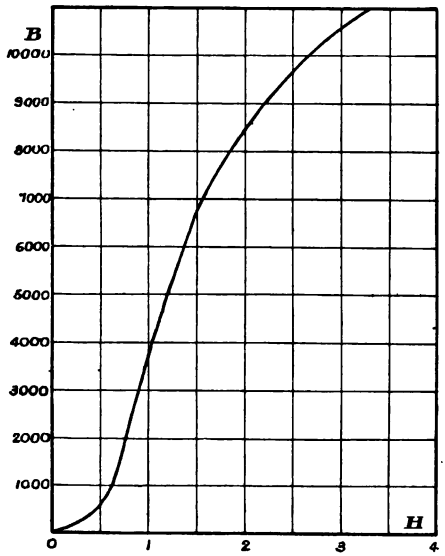

FIG. 94.

in the high density case, although less iron is required in the movement, thereby reducing power consumption and friction loss, it is found that the instrument will depend on the instantaneous value of the current rather than on the R.M.S. value. Thus this form of instrument will be seriously affected by changes in wave form, see Fig. 95, where currents possessing wave forms of the same constants respectively as those used in the test on induction instruments, page 87, are employed. The instrument had only a small amount of iron in its movement, which was consequently highly saturated. In the low

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density case there will necessarily be increased power consumption, but the forces acting on the moving iron will now be nearly proportional to the square of the current, the instrument then reading the R.M.S. value.

4. Since the current in the main coil will depend on its impedance, any variation in the frequency will produce a corresponding alteration in the current, consequently the readings will be inaccurate if the instrument has not been calibrated at the frequency for which it is to be used. It is therefore necessary, when designing the magnetising coil, to keep the coefficient of self-induction as low as possible, and

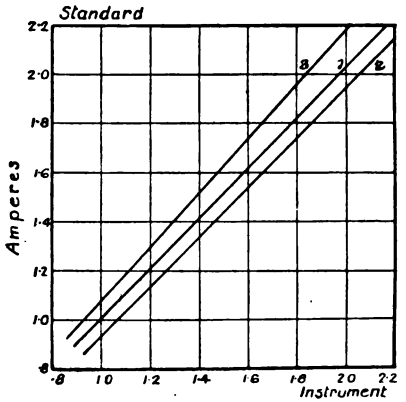

FIG. 95.

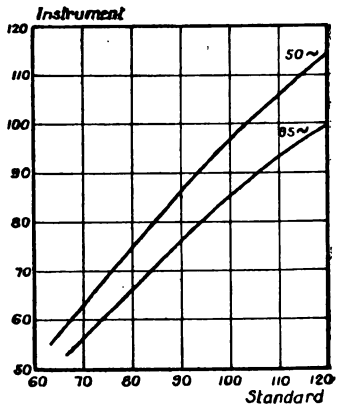

FIG. 96.

to increase the resistance as much as is reconcilable with low power consumption. Fig. 96 shows a very bad case of frequency error in a voltmeter. Modern instruments can now be obtained which are practically free from this source of error.

When these instruments are to be used on both continuous current and alternating current circuits, some makers shunt the magnetising coil with a small choking coil capable of carrying about 5 per cent. of the working current when continuous current is used, but owing to the choking effect of the auxiliary coil it only carries 2 per cent. when employed on alternate current circuits, thus providing an additional 3 per cent. to overcome the increased impedance in the main coil.

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The instruments just described are the commonest of this system, i.e. moving iron system, but there is frequently met with another type, which although belonging to this system does not work on the electromagnetic principle.

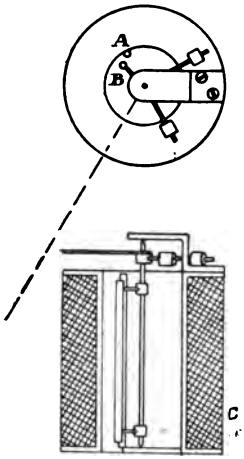

FIG. 97.

Construction.—Within the coil C, Fig. 97, which is similar to that described page 105, are placed two pieces of soft iron, one of which is fixed A, the other B is attached to a spindle, which is pivoted so as to be able to move through a fairly large angle. Fig. 98 shows a photo of the movement of this instrument as put on the market by Messrs. Nalder Bros. and Thompson, but Fig. 99 shows a somewhat different construction, adopted by Messrs. Johnson and Phillips, a small piece of iron being fixed outside the tube, and the tube then put in a coil.

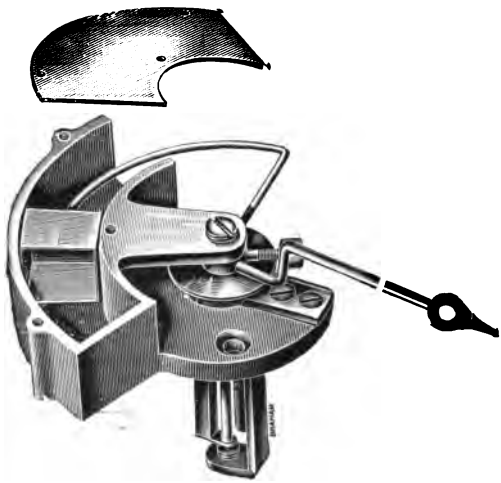
FIG. 98.

Theory.—Since two pieces of soft iron are placed side by side in the same field, they will have induced in them at the

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same ends a like polarity, either a north or a south pole, according to the direction of the flow of the current in the coil, and they will therefore repel one another. This force of repulsion will be proportional to the product of the strengths of the induced poles, consequently, if these are made nearly equal, this instrument will also follow, very approximately, a square law.

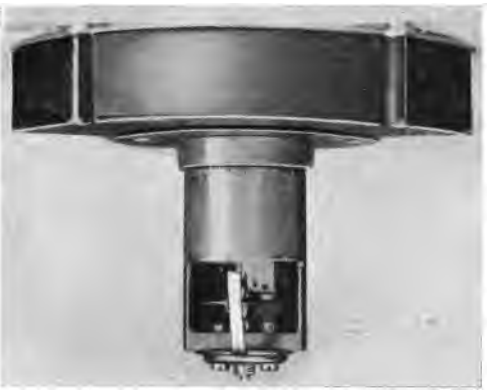

FIG. 99.

The errors to be guarded against in these instruments are practically the same as those given on page 108, and need not be reconsidered here.

c. HORSE-POWER METER.

The power of a current or the rate at which a current does work in a circuit, is measured by the product of the current into the voltage (CV), that is the watts, according to the definition of the watt already given. But 746 watts is the electrical equivalent of mechanical horse-power. Therefore $\frac{CV}{746}$ will be the horse-power expended in the circuit.

Now if the voltage remains constant or practically so, the power becomes proportional to the current, consequently an ammeter may be calibrated as a horse-power meter. Such an

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instrument was found desirable in connection with the commercial use of motors, as it indicates without calculation what the motor is doing.

Since it has been assumed that the voltage must be constant, this instrument can only at its best be approximately accurate, as in no circuit in which it is likely to be used is it possible to maintain the voltage invariable for any length of time. A further disadvantage occurs when these instruments are used on alternating current circuits since the horse-power will now be proportional to $C V \cos\phi$. An instrument could of course be calibrated so as to read correctly if $\cos\phi$ were known, but as this is rarely constant, these instruments when used in alternate current work can only at their best be good indicators.

d. Ohmmeters.

These instruments are ammeters calibrated in ohms, and generally used to measure insulation resistance. The insulation resistance of a circuit should be perfect or nearly so, and as a consequence, the leakage currents which are likely to flow will be very small, therefore the most suitable instrument to use is a milli-ammeter.

The construction of this instrument will be the same as a high resistance ammeter of this system. Since the instrument is to be used to read very small currents, it must have a large number of ampere-turns on the magnetising coil in order to get the necessary pull. From this it follows that the resistance of the instrument must be high, and, further this is essential should, by chance, the insulation resistance become nil, because then the instrument would be directly across the mains (see Fig. 100). Therefore, the gauge of wire used on the magnetising coil must be small, usually, it is about No. 36 S.W.G. This instrument is connected as shown in Fig. 100, in which E represents a good earth connection for middle point of switch K. R_1 and R_2 are the resistances to earth of the two mains 1 and 2 respectively.

Theory.—Supposing the voltage of the system to remain constant, then the current flowing through the instrument is

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inversely proportional to the resistance of the circuit, that is, to R + G, where R = resistance of the insulation in ohms, and G = resistance of the instrument in ohms. R is usually very many times greater than G, so that for practical purposes G may be neglected. Thus instead of calibrating the instrument as an ammeter, it may be calibrated in ohms, to read the insulation resistance, since for any variation in R, the pointer must change its position.

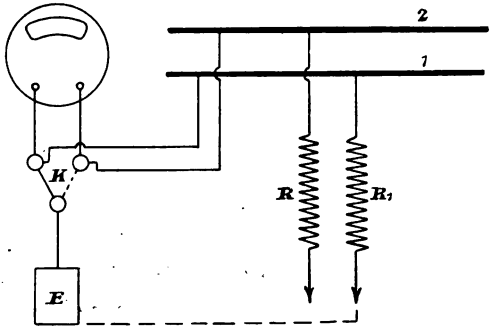

FIG. 100.

Error.—Since this instrument is made on practically identical lines with electromagnetic ammeter described on page 105, it must suffer from errors to which that instrument is subject. But these errors are small compared with the error introduced by the voltage of the mains, if this voltage is not constant and the same as that used in calibration.

Advantage.—As in the case of the horse-power meter, the only advantage which can be claimed for this instrument is that it gives a rough-and-ready indication, at a low initial outlay. This instrument is another form of leakage indicator, but not so accurate as the instrument made for that purpose.

e. LEAKAGE INDICATORS.

These instruments may be used on either alternate or continuous current circuits. Reliable readings, however, cannot be obtained from them when used on the former, owing to the fact that capacity or displacement currents are also

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measured by the instruments, and these mask the true leakage currents, often to such an extent as to make the readings of no use. Nevertheless, there is this advantage about them that they indicate any serious fault which may occur on the system, and thus allow the attendant to take the necessary precautions for the prevention of damage to plant, etc. When it is known on which main the fault exists the insulation resistance may be found by means of any of the ordinary testing sets while the plant is not running, or the exact position of the fault may be located by means of one of the well-known tests as Varley's, Blavier's, etc.

Construction.—In many respects these instruments are like type A. They consist of an ordinary type C movement, but with a winding of fine wire, so that the instrument will read in milli-amperes. The other parts of their construction are the same as in an ammeter or voltmeter of this system.

For instruments which are to work off one phase only, a central zero scale is provided ; but for other circuits the scale

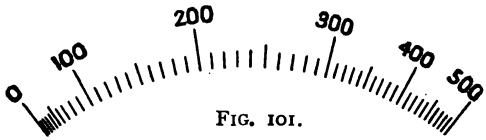

FIG. 101.

is as in ordinary instruments. Fig. 101 will convey some idea of the spacing of the scale divisions of this type of instrument.

In two-wire continuous current and single-phase systems, the connections are the same as those shown in Fig. 40. In two-phase circuits two instruments are usually employed, one for each phase, in which case the connections are similar to those for a single-phase instrument. In three-phase circuits with the neutral point inaccessible, one instrument can be used if an artificial neutral point is made. Normally the switch remains on the neutral point as shown in Fig. 102. When readings are to be taken, it is successively passed on to stops 1, 2 and 3, thus testing the three mains.

To understand what the readings of the instrument indi-

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cate, let us consider the case of a short on No. 1 main. Since the instrument circuit has a high resistance and is in parallel with the leakage path of No. 1 main, it follows that if there is a short on this main, that is, if the resistance of the leakage path is low, then the reading on the instrument will either be zero or else very small. When the switch is passed to stops 2 and 3, the readings will be very large since the instrument is now practically connected across the mains 1 and 2, and 1 and 3 respectively. This is the worst possible case which can occur, but if leaks from the mains are in existence, the smallest reading of the instrument when tried on stops 1, 2 and 3, will generally indicate the main on which the insulation is worst. It is not difficult to see that under certain conditions the readings of these instruments will be difficult to interpret.

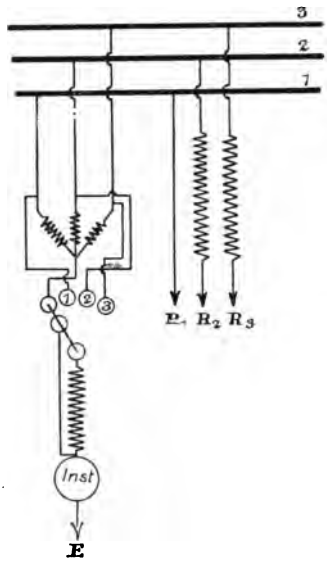

FIG. 102.

If, however, the neutral point is available, then an ordinary ammeter is connected between it and earth, thus indicating the sum of the leakage currents. A switching arrangement similar to that used in the previous case cannot be used here, since it would interrupt the continuous earth-connection from the neutral.

There is another method in common use for measuring the leakage currents from an alternate current system. This is to superpose upon the circuit a continuous current of small magnitude, and measure the amounts which leak to earth by means of a milli-ammeter. This method of testing gets rid of the disadvantages met with when measuring the alternating current leakage, but the insulation resistances can only be obtained from the readings with considerable trouble.

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f. Frequency Meter.

Construction.—The constructional idea upon which this instrument is designed is the same as that used in the type B_2 frequency meter. Two voltmeter movements are used. These two movements are so arranged that the action of the one opposes that of the other, while both are communicated to a common spindle which also carries the usual balance weights and pointer. Thus the pointer will simply show the difference between the two forces due to the separate movements, and it is easily seen that no controlling force is needed. The magnetising coils, which are the same as for the voltmeter described on page 105, are connected in parallel, one branch of which is made highly inductive by means of a choker, and the other made practically non-inductive by the addition of a non-inductive resistance. This parallel circuit is put across the mains.

Theory.—If the frequency change, then the pull on the moving iron of the inductive branch will change also, while that of the other will remain practically constant. But the pulls exerted by these coils for any particular frequency will cause the moving system to come to a state of balance. It follows therefore that for every change of frequency a new position of balance will be taken up, and thus the pointer will indicate any variation in the frequency.

Errors.—The errors which one would expect to find in these instruments are the same as in the moving iron voltmeter given on page 108, but of course No. 4 can no longer be counted as one. Errors would be introduced by variations in voltage if these were large, but they may be neglected if the voltage variation does not exceed $\pm$ 10 per cent.

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CHAPTER VIII.

ELECTRO-THERMIC PRINCIPLE.

HOT-WIRE SYSTEM.

PROBABLY the first commercial instrument to be built on this principle was the voltmeter designed by Major Cardew about 1887. Since that time, many modified forms of his well-known construction have appeared on the market, but none of them have ever been largely used in England. From the many drawbacks which the instrument possesses, it is remarkable that it should have been used as largely as it has been. But the reason for this may be put down to the fact that it was, when it first appeared, about the only satisfactory dead-beat instrument which could be obtained for use on alternate current circuits.

a, *b*. AMMETERS AND VOLTMETERS.

Construction.—These instruments are usually made of a wire, the temperature coefficient of which is negligible and the specific resistance high, stretched between two supports with some mechanical arrangement to take up the sag in the wire caused by its expansion when a current flows through it. Whatever arrangement is used to take up this sag, it is connected with the pointer, thus causing the instrument to show the expansion in the wire due to a definite current. The working wire is generally made of platinum silver, but any alloy which conforms with the conditions stated above, will do. The size of wire used may vary according to the range of instrument wanted, but it is found in practice that a wire of 0·0025 inch in diameter is the smallest which can safely be employed. With a small wire there is always the danger

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that the instrument may be burnt out by a sudden overload. Further, it is more difficult to protect such an instrument with a fuse, since in the fuse a wire considerably smaller than the working wire has to be employed, and when this is the case, very careful handling of the instrument is necessary. On the other hand, when a large wire is used, it possesses less resistance for the same length, and that, with an increased radiation surface, the result being that the pointer takes longer to reach its proper position.

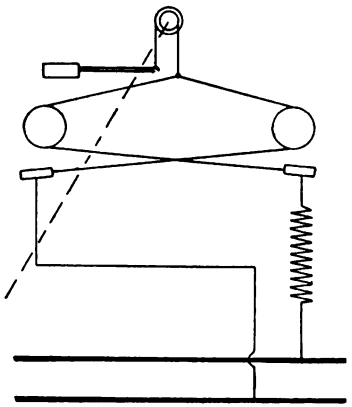

FIG. 103.

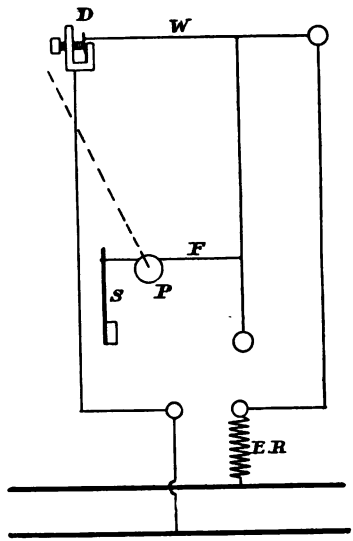

FIG. 104.

Instruments constructed on this principle readily lend themselves to use as voltmeters, see Figs. 103 and 104, since the wire itself must have a high resistance, and another high resistance E R can easily be put in series with it in order to make the readings proportional to the voltage. In the case of ammeters a slightly larger wire than 0·0025 inch in diameter is used, which is the size of wire commonly met with in voltmeters. This larger wire about 0·04 inch in diameter, is divided up into several parts which are connected in parallel, see Fig. 105, so that the combination is now capable of carrying 5–10 amperes as its normal load. All ammeters are sup-

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plied with fuses which are made of a wire of such diameter that it melts when carrying a little over the maximum load. For ammeters above 10 amperes, shunts such as described on page 25 require to be used, the terminals of the instrument being connected to the two blocks of the shunt. Since the wire will expand or contract for any variation in the temperature of the outside air, it is necessary to attach some device to the instrument, so that this sag may be taken up. Usually, the supports carrying the wire W are fixed to a base of a material whose coefficient of linear expansion is the same as

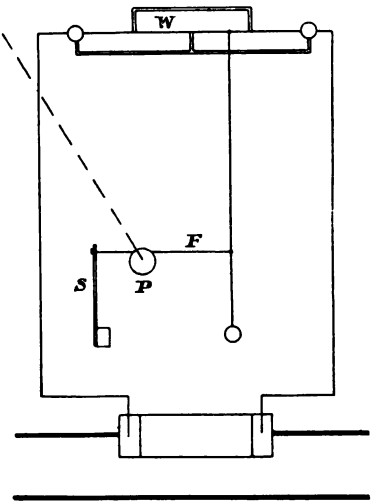

FIG. 105.

that of the wire. But, as a rule, a further piece of apparatus D Fig. 104 is supplied which can be used by the attendant to take up any permanent set which the wire may have acquired. The pointer and balance weights are fixed to a spindle which is pivoted between jewel centres as described for type A instruments, page 40. On this spindle is generally fixed a small pulley P round which is brought the fibre F which takes up the sag in the working wire, one end of the fibre being fixed to a spring, so that it is always under a constant tension. When the wire expands, the fibre is pulled by the spring, so as to take up the sag, thus rotating the spindle through

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an angle proportional to the expansion of the wire. These instruments will be quite unaffected by stray fields, so that an iron case is not essential. Though the instruments are usually very dead-beat, yet additional damping is sometimes required, in which case any of the methods described on page 24 may be used, and of these magnetic damping is the most suitable.

Theory.—Let

C = current in amperes flowing in hot wire
T_0 = initial temperature of wire in ° C.
T = final temperature of wire in ° C.
R_0 = initial resistance of wire in ohms at temp. T_0.
R = final resistance of wire in ohms at temp. T.
t = time current flows in secs.
σ = temperature coefficient of wire.

Then by Joule's law, the quantity of heat in calories possessed by the wire due to the passage of the current for time $t = C^2 R t \times 0{\cdot}239$.

But at the same time that heat is being given to the wire it is also giving up heat by radiation and convection to the surrounding medium.

The quantity of heat given up by unit surface in unit time being proportional to the difference between the final and initial temperatures, may be represented as $k_0 (T - T_0)$. Consequently, since $t = 1$

$$\therefore \qquad 0{\cdot}239\ C^2 R = k_0 S (T - T_0)$$

where S = total radiating surface of the wire.

$$\text{Now } R = R_0 \{1 + \sigma (T - T_0)\}$$

$$\therefore \quad 0{\cdot}239\ C^2 R_0 \{1 + \sigma (T - T_0)\} = k_0 S (T - T_0) \quad (1)$$

Now, if l_0 = original length of wire, a = coefficient of linear expansion of the material of the wire, and b = expansion of wire due to rise in temperature of $(T - T_0)$ ° C.

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Then $$b = a\, l_0\, (T - T_0)$$

$$\therefore \quad T - T_0 = \frac{b}{a\, l_0} \quad . \quad . \quad . \quad . \quad (2)$$

substituting this in equation (1), we obtain

$$0{\cdot}239\, C^2 R_0 \left\{1 + \sigma \left(\frac{b}{a\, l_0}\right)\right\} = k_0 S \frac{b}{a\, l_0}$$

or,

$$C^2 \left(1 + k_1 \frac{b}{l_0}\right) = k_2 \frac{b}{l_0}$$

where

$$k_1 = \frac{\sigma}{a}$$

and

$$k_2 = \frac{k_0 S}{a} \cdot \frac{1}{0{\cdot}239\, R_0}$$

$$\therefore \quad C^2 = \frac{k_2 \frac{b}{l_0}}{1 + k_1 \frac{b}{l_0}}$$

and since $\frac{b}{l_0}$ is usually very small, we may write

$$1 - k_1 \frac{b}{l_0} \quad \text{for} \quad \frac{1}{1 + k_1 \frac{b}{l_0}}$$

$$\therefore \quad C^2 = k_2 \frac{b}{l_0}\left(1 - k_1 \frac{b}{l_0}\right)$$

$$= k_2 \frac{b}{l_0} - k_1 k_2 \left(\frac{b}{l_0}\right)^2$$

Now the instrument is so arranged that its readings are proportional to the expansion of the wire, consequently there is in the last equation a connection between the current and the deflection. If, as might possibly be done, the second term $k_1 k_2 \left(\frac{b}{l_0}\right)^2$ were made negligible, then the deflection of the instrument would be proportional to C^2, but in practice, this is only approximately so.

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The quantity k_0 is called the emissivity of the wire, and varies with the temperature, so that the above equations can only be assumed as correct when the temperature change is small. Further from the great difficulty there is of obtaining accurately this quantity, the result deduced is of little practical value, but it serves to show what should theoretically be the case.

Errors. — The following sources of error may cause trouble :—

1. Variation of zero.
2. Creeping in the readings.
3. Shunt troubles.

1. There is always a great deal of uncertainty about the zero which may require to be attended to every time the instrument is put in the circuit. This may be due to, either variation in the temperature of the surrounding air, or to the fact that the wire has not shrunk back to its original position, but has acquired a permanent set. This error may be eliminated by means of the device mentioned in the construction, page 121.

2. This will result if the coefficient of linear expansion of the base is not the same as that of the wire itself, for the method of preventing this, see construction, page 121. It may further result from sudden changes of temperature, since the wire will much more readily adapt itself to these than the base. But as this is never very large and soon disappears, it may be neglected.

3. Errors here introduced by the shunt will be the same as numbers 5 and 6, page 43, and must be avoided in a similar manner to that described there.

Advantages.—1. The principal advantage of this type of instrument is its freedom from serious error. The readings are entirely free from errors arising from frequency, wave form, and stray magnetic fields, while the error due to self-induction is so small as to be negligible.

2. Further, they can be used in either alternating current or continuous current circuits without recalibration, giving the

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same accuracy on both. This is of great use to the maker, since he can calibrate the instrument with a continuous current.

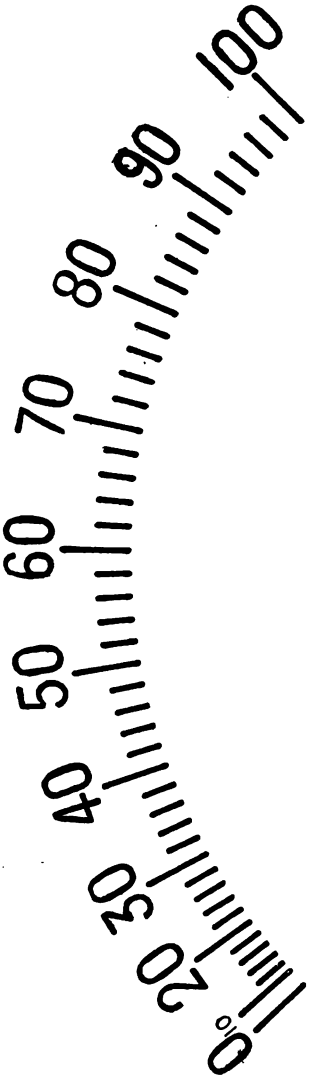

Fig. 106.

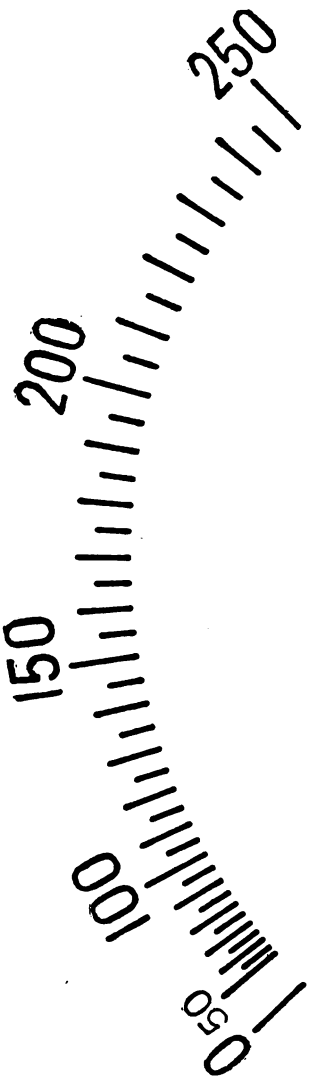

Fig. 107.

Disadvantages.—1. As might be expected, the power consumption is very large, see Table III.

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2. There is always the risk of the wire being fused due to an overload. Although the instrument-wire is usually made to stand an overload of 100 per cent. if gradually applied, it is found that a sudden overload nearly always destroys the wire.

3. Since the instrument depends on a square law, the scale will also follow the same law. Consequently the readings will be very close together at the bottom and far apart at the top of the scale. This is certainly an advantage in the case of voltmeters, but is anything but an advantage for ammeters. The lowest reading which can be taken on the latter being about 10 per cent. of the maximum.

The truth of these remarks is well shown by Figs. 106 and 107, which are the scales obtained from an ammeter and voltmeter respectively.

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CHAPTER IX.

ELECTROSTATIC PRINCIPLE.

MOVING VANE SYSTEM.

THIS instrument is founded on the principle enunciated on page 4. The first practical instrument was Lord Kelvin's electrostatic voltmeter for high pressures. For switchboard work there is not a great deal to recommend this instrument, since on high pressures, where it would most likely be employed it is now possible to use type A for continuous current circuits or types B and C for alternating current circuits in conjunction with potential transformers.

a. VOLTMETER.

Construction.—This instrument consists of an air-condenser, whose capacity is varied according as a light vane acting as one plate of the condenser moves nearer to or away from a pair of fixed blades acting as the other plate.

There are two forms which are commonly met with, one in which the blades are curved, the other in which the blades are flat. In the first form the parallel fixed blades are bent into the shape of a cylinder, the moving vane being also of cylindrical shape, but of such a radius that when pivoted at the centre of curvature of the fixed blades, can move between them equidistant from both. In the second form, the blades and vane are flat, Fig. 108, and parallel to one another, the vane V being, of course, equidistant from both blades F. The vane is generally made of aluminium in order to reduce the weight of the moving parts, and is given such a shape as will produce the best obtainable form of scale. The fixed

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blades are brought as near together as permissible with the voltage on which the instrument is to be employed, and are completely covered with mica, so as to reduce the chances of sparking. The spindle to which the moving system is connected is made as light as possible. It carries the pointer and balance weights, and is either pivoted between jewels or allowed to rest on knife edges. The great object in the design of the moving part is to reduce friction to a minimum, as the available moving force is very small. In order to increase this moving force as much as possible, the fixed blades are brought near together, but as this increases the risk of breakdown due to sudden rise of voltage, to safeguard the instrument, a spark gap is sometimes put in parallel with it across the mains, but with a narrower gap than exists between the vane and the fixed blade. This is, however, found

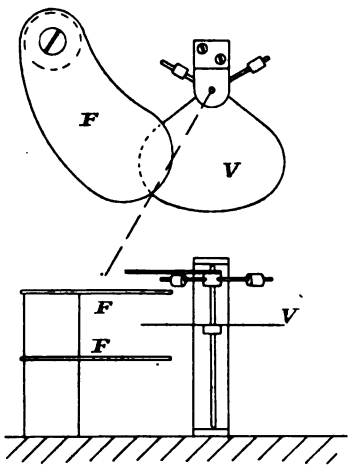

FIG. 108.

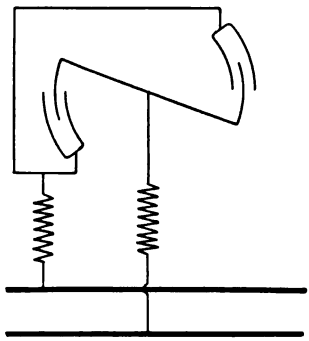

FIG. 109.

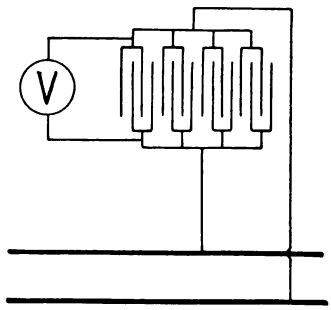

FIG. 110.

unsatisfactory, as the silent discharge produces ozone, which rapidly destroys the insulation of the instrument. There is now much more frequently found either a high non-inductive

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resistance, or a fuse of very fine wire substituted for the spark gap, see Fig. 109. The control most commonly met with is that due to gravity, but a spiral spring control is sometimes employed. Owing to the lightness of the movement the instrument is fairly dead-beat, but an additional damping force 1 or *2a* is usually supplied. This instrument is satisfactory up to about 5000 volts, but above this trouble is experienced in properly insulating the working parts. To

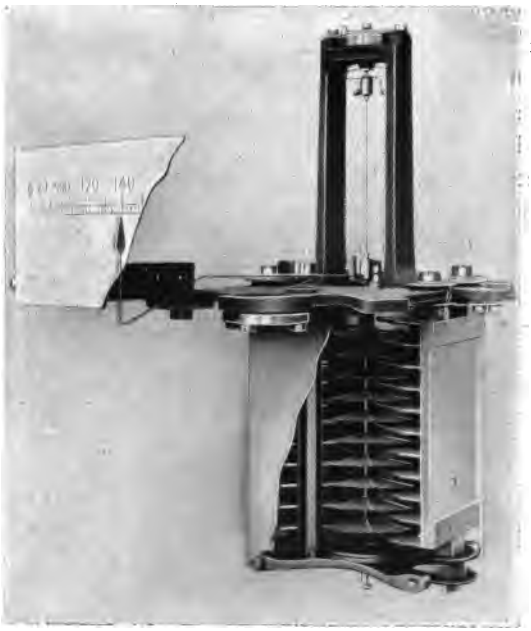

FIG. 111.

increase its range a battery of condensers is used in conjunction with it, see Fig. 110. The condensers are all in series and equal in capacity, the number used depending on the voltage to be applied to their terminals. If this battery of condensers is connected across the mains, the voltage across any one condenser will be inversely proportional to the number in series, so that if the voltmeter is applied to the terminals of one of them, it may be calibrated to read directly the voltage on the mains.

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To measure low pressures, another form of the instrument has to be adopted. In this multicellular voltmeter, see Fig. 111, a number of blades similar to those just described are connected in parallel, and have a vane moving between each pair. It is thus possible to obtain the necessary power required to work the instrument for pressures as low as 40 volts.

The pot used for this type of instrument was, until recently, nearly always made of ebonite or stabilit, but by very carefully insulating all the working parts, it is quite possible to use an iron or brass pot, at any rate for voltages up to 1000. There are only two terminals on this instrument, one being connected to the moving vane system, and the other to the fixed blades, through fuses if these are used. These two terminals are connected one to each main of a continuous current circuit, or across one phase of an alternating current circuit.

Theory.—Let V = Potential differences between vane and blade.

D = deflection in degrees.

C_0 = change in capacity of moving system for unit deflection.

From the electrical side, the energy of the system is

$$= \tfrac{1}{2} C V^2 \qquad \text{where } C = \text{capacity}$$
$$= \tfrac{1}{2} C_0 D \,.\, V^2$$

If the instrument is spring controlled, then this energy is balanced by the energy stored by the spring.

If F_0 = force exerted by the spring per unit deflection, then average force for a deflection of $D = \tfrac{1}{2} D F_0$, and consequently, energy stored is $= \tfrac{1}{2} F_0 D^2$.

$$\therefore \qquad \tfrac{1}{2} C_0 D V^2 = \tfrac{1}{2} F_0 D^2$$

$$D = \frac{C_0}{F_0} V^2$$

If F_0 and C_0 are constant, then $D = K V^2$, where K is a constant.

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It follows from this that the scale should follow a square law, but in practice it is found that this is not the case, although approximately so. The reason for this is not far to seek, for although F_0, for most modern springs, is practically constant throughout the range of deflection, C_0 is a variable, depending principally on the shape and arrangement of the blades and vanes.

Except in multicellular instruments, F_0 is usually very large compared with C_0, so that in order to obtain a satisfactory deflection V must be great.

In the case of an instrument in which a gravity control is employed instead of a spring control, a similar line of argument may be employed.

Here, however, the energy which balances the electrical energy is obtained from the force of gravity, and the vertical distance through which the centre of gravity of the vane moves from the "at rest" position to that representing the deflection D.

Errors.—These may be due to—

1. Electrostatic fields.
2. Stray magnetic fields.
3. Leakage in the condensers.

1. If the pot is made of a non-metallic material, it will be found that when it is rubbed a static field is set up. This brings into play forces not taken account of when calibrating the instrument, the result being that the instrument becomes inaccurate until the charge produced by the rubbing is dissipated. In order to overcome this trouble a coat of a conducting varnish is generally given to the pot before it leaves the works.

2. Eddy currents will be set up in the vane and blades by stray magnetic fields. A small error is thus introduced which is in most cases so small as to be negligible.

3. If any of the condensers leak, the voltage across their terminals will not be the same as before, hence the proportionality of the voltage across the instrument to the voltage of the mains may be altered, and the calibration thus made use-

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less. This error may be overcome by carefully designing the condensers so as to reduce leakage to a minimum. If the same condensers are used, and in the same manner, for work as when calibrated no error would be introduced.

Advantages.—1. Their calibration is not likely to alter after long use.

2. Their power consumption is nil.

3. They are independent of temperature changes.

4. They will measure with equal accuracy on either continuous or alternate current systems.

Disadvantges.—1. A short and uneven scale, see Fig. 112, on which the divisions are close together at the bottom and

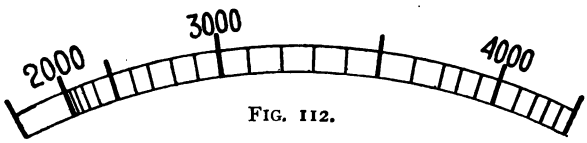

FIG. 112.

opened at the top. This can be partially got over by altering the shape of the vanes, but this only affects the scale to a small extent. Prof. Ayrton suggested in 1893 that a condenser might be placed in series with an electrostatic voltmeter, the capacities being about the same. The voltage to be measured is applied to the terminals of the combination. It is known that the voltage will divide itself between the condenser and the voltmeter inversely as their capacities. Thus when the moving vane is at its farthest out position, the capacity is least, consequently the voltage is greatest, and as the moving vane is attracted inwards between the fixed blades, the voltage will gradually decrease. Hence the readings will be opened out at the lower end of the scale, and will thus be rendered nearly equal throughout the length of the scale.

2. It is ill-adapted for portable use, and greater care has also to be taken with the switchboard form than with other instruments.

3. The great disadvantage of the instrument is the weakness of the effective moving force.

4. Large cost.

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b. Leakage Indicators.

For high-tension mains where a grave risk would be incurred if the mains were connected to earth through an ordinary instrument, this type of leakage indicator is very suitable. Previous to the use of this type for the purpose, it had been customary to employ a voltmeter worked off the secondary of a transformer. This method enabled ordinary voltmeters to be used.

Construction.—There are to be met with in practice various forms of this instrument which do not differ greatly from one another. They will be described below under the system on which they are commonly used.

Continuous Current and Single-phase.—Here two sets of quadrants or blades are used between which the needle moves. The sets are connected one to each main, sometimes through condensers, but more frequently through resistances. The needle in this instrument is connected to earth and is so placed that it is acted on by both sets of blades. The deflection will be proportional to the algebraic sum of the leakage currents, inclining to one side or the other of the central zero as the insulation resistance of the one main is greater or less than that of the other.

Two-phase.—Here two single-phase instruments are used.

Three-phase.—In this case three single-phase instruments are generally employed. There are, however, instruments to be met with which have all three movements in one case, and instead of using six sets of quadrants or blades each needle is so arranged that only three sets require to be used, and three scales to be provided.

As has been stated under type C leakage indicators the readings of instruments on two- and three-phase circuits cannot be relied on, so that these must needs be regarded as indicators, and some other method, such as has already been suggested, be employed to find the actual condition of the mains. Fig. 113 shows a central zero electrostatic leakage indicator scale, and gives some idea of its arrangement.

The insulation resistance of the mains cannot be obtained

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directly from the readings of any of these instruments. In the case of the continuous current system it is possible by shunting the instrument with a known resistance, and taking

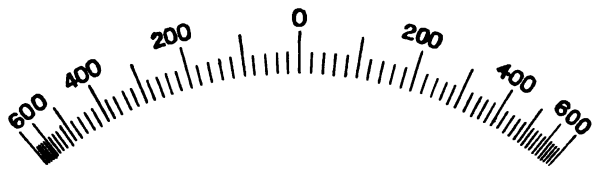

FIG. 113.

a second reading (the first being on the unshunted instrument) to calculate the resistance of the insulation. But this is unsuitable for switchboard work, so that on the whole these instruments must be considered only as indicators and nothing else.

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CHAPTER X.

RESONANCE PRINCIPLE.

VIBRATING REED SYSTEM.

THE principle of resonance has as yet been used in electrical engineering, only for the measurement of the frequency of an alternating current. An instrument constructed on this principle is very convenient, as it obviates the difficulty of making a calculation. The frequency of the current supplied by an alternator may be obtained from the formula

$$f = \frac{p}{2} \times r.p.s.$$

where

f = frequency in cycles per sec.
p = no. of poles.
$r.p.s.$ = no. of revolutions per second.

But as a rule a tachometer is a difficult instrument to read, and a considerable amount of error is liable to creep in by this method. It was to overcome this difficulty that the instrument about to be described was designed.

Construction.—Probably the earliest form of instrument built on this principle was that introduced by Mr. A. Campbell, in which was employed a steel reed whose length could be varied. The reed was put into vibration by an electromagnet, the winding of which carried the current whose frequency was to be measured. The reed was set in such a way that it would vibrate at a lower frequency than that intended to be measured, then its length was gradually decreased until the instrument emitted a sharp jarring noise. By the mechanism used for altering the length of the reed a pointer was made to

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move over the scale, so marking the required frequency, which was indicated to the ear of the operator when the jarring noise occurred.

The latest form of this instrument consists in employing a number of steel reeds R, each tuned to vibrate at one frequency only. These reeds are fixed around, but at a distance of about 0·25 inch away from, the periphery of the pole of an electromagnet, as shown in Fig. 114.

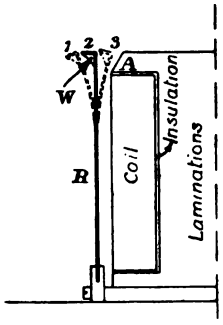

FIG. 114.

They may be rigidly fixed to the same base as this magnet, or may be fixed to a separate base which is set into vibration by the magnet; an instrument of the latter form is shown in Fig. 115.

The magnet consists of a laminated iron core, with one pole A shaped as shown in Fig. 114, on the core of which is wound a large number of turns of wire, whose gauge will depend on the voltage on which the instrument is to be used.

The reeds are made of well-annealed strip steel, which possesses as an essential quality a natural frequency which will remain constant for an indefinite time. In thickness, they are about 0·025 inch, and from 0·125 to 0·1875 inch wide. The length is constant, and is calculated to give approximately the highest frequency commonly employed in practice. In order, therefore, that the reeds may have different periods of vibration, the free end W is weighted, usually with solder. The larger the weight added, the slower are the oscillations. In this manner almost any frequency required can be obtained with one standard length of reed. The usual difference of frequency employed between each consecutive reed is 1 per cent. for frequencies in the neighbourhood of the standard, but this is by no means fixed, as it can be easily altered to suit the accuracy with which it is desired to read the frequency.

The scale is constructed of the usual Bristol board backed with a metal plate, and the whole instrument is fixed in an

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iron or brass pot; Fig. 116 shows the outside view of an instrument built on the construction shown in Fig. 114.

FIG. 115.

FIG. 116.

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The two ends of the magnetising coil are connected to two terminals on the instrument, these in turn are connected one to each main of the system through a high resistance, so that the instrument is put across the mains, see Fig. 117.

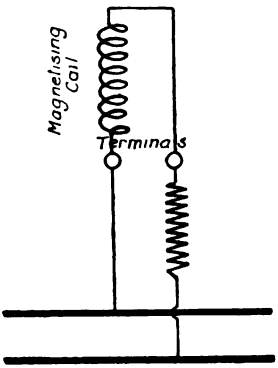

FIG. 117.

Theory.—The field set up by the current in the winding of the electromagnet is an alternating field of the same frequency as the current, consequently the attracting force exerted by the magnet on the reeds will reach a maximum twice in each cycle. Let the reed have a frequency of vibration such that it makes one complete vibration for a variation in the attracting force of from zero to maximum. Now suppose that the reed is in the position marked 2 in Fig. 114 when the attracting force is a maximum, then by the time this force is again at its maximum, the reed will have made one complete vibration, and be in the same position. Further, the sum of the instantaneous attracting forces will be much greater while the reed is travelling from 1 to 3 than from 3 to 1. Now it can easily be seen that each time the reed swings from 1 to 3 it will receive a fresh impulse, which will keep it going at a definite speed. Successive impulses given to the reed coincide with its natural vibration, so that the amplitude of the swing is augmented till the air resistance and molecular friction of the spring, resisting the motion, are sufficient to balance the augmenting force. Thus for any given frequency only one reed will give a large vibration, and is consequently easily picked out from the four or five reeds vibrating.

If the electromagnet be wound with another coil having the same number of ampere turns as the winding already on it, but in this case fed with continuous current, the range will be doubled, since this secondary winding will polarise the magnet, and thus wipe out one attraction and double the

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other. Thus if one of these instruments were put on 50 ~ circuit, the original 25 ~ reed would vibrate.

Errors.—The errors which this instrument is liable to in calibration and construction are so trifling that it can easily be made to read within 0·2 per cent. of accuracy.

Advantages.—The great advantage possessed by this instrument over every other type of switchboard instrument is the ease with which a reading may be taken. Another advantage is that intermediate frequencies can quite readily be estimated to within $\frac{1}{4}$ per cent. if the consecutive reeds have a difference of 1 per cent.

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APPENDIX.

The abbreviations which are used in the following list of references have meanings as given below :—

Abbreviations.	Full Title.
Am. Elect. . . .	American Electrician. New York.
Am. Jour. Sc. . .	Proceedings of the American Association for the advancement of Science. Philadelphia.
Elect.	Electrician. London.
Elect. Eng. . . .	Electrical Engineer. London.
Elect. Jour. . . .	Electric Journal. Pittsburg.
Elect. Mag. . . .	Electrical Magazine. London.
Elect. Rev. . . .	Electrical Review. London.
Elect. Wld. . . .	Electrical World. New York.
Elek. Zeit. . . .	Elektrotechnische Zeitschrift. Berlin.
Engin.	Engineering. London.
Jour. Franklin Inst.	Journal of the Franklin Institute. Philadelphia.
L'Élect.	L'Électricien. Paris.
L'Écl. Élect. . .	L'Éclairage Électrique. Paris.
Phil. Mag. . . .	Philosophical Magazine. London.
Proc. A.I.E.E. . .	Proceedings of the American Institution of Electrical Engineers. New York.
Proc. I.E.E. . .	Proceedings of the Institution of Electrical Engineers. London.
Proc. Jun. I.E.E. .	Proceedings of the Junior Institution of Electrical Engineers. London.
Proc. Civil Eng. .	Proceedings of the Institution of Civil Engineers. London.
Sc. Abs. . . .	Science Abstracts. London.

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LIST OF REFERENCES.

	Name of Paper.	Author	Where to be Found.	Date
	Electrical measuring instruments	Sir W. Thomson .	Elect , xviii. 541 .	1887
	Ditto	J. Swinburne . .	Proc. Civil Eng., xc. 1	1892
	Kelvin's patents . . .	M. Maclean . .	Elect. Eng., xxi. 231, et seq.	1898
	New alternate current instruments	G. Benischke . .	Elek. Zeit., xx. 82	1899
	Electrical measuring instruments	J. Stevens. . .	Jour. Franklin Inst. cl. 44	1900
	Electrical measuring instruments at Paris Exhibition (German)	H. Armagnat .	{L'Écl. Élect., xxv. 329}	1900
	Ditto (French, and others)	H. Armagnat. .	L'Écl. Élect., xxvi. 77, 198	1901
	Instruments et méthodes de mesures électriques industrielles	H. Armagnat. .	Book. Paris . .	1902
	Electrical engineering measuring instruments	G. O. A. Parr . .	Book. London .	1903
	Direct reading measuring instruments for switchboard use	{K. Edgcumbe . F. Punga . . .}	Proc. I.E.E., xxxiii. 620	1904
	Some recent electrical measuring instruments	K. Edgcumbe .	Proc. Jun. I.E.E., xvi. 175	1906
	New iron-cored instruments for alternate current working	W. E. Sumpner .	Proc. I.E.E., xxxvi. 421	1906
	New D.C. switchboard instruments	A. O. Benecke .	Elect. Wld., xlvii. 745	1906
	Simplex instruments (American)	..	Elect. Wld., xlv. 911	1905
	Westinghouse K-type instruments (American)	..	Elect. Wld., xlv. 312	1905
	Richard's instruments (French)	..	L'Écl. Élec., xlv. 206	1905
	Ammeters and Voltmeters.			
	Calibration of ammeters and voltmeters	L. A. Freudenberger	Elect. Wld., xlv. 302	1905
B_2	Correcting induction voltmeters for temperature changes	..	Elec. Jour., i. 555	1904
	Correcting induction voltmeters for frequency variation	..	Elec. Jour., i. 427	1904
	Idle-current ammeter .	..	Elect., lv. 177, 227, 269	1905

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LIST OF REFERENCES.—*continued.*

—	Name of Paper.	Author.	Where to be Found.	Date.
	Correcting induction instruments for variation in temperature	..	Engin., lxxxiii. 99	1907
	Improving scale of induction instruments	..	Engin., lxxxiii. 225	1907
	A new form of induction ammeter	P. MacGahan .	Elect. Jour., iv. 113	1907
C	Alternate current compensated voltmeters	H. Young. . .	Am. Elect., xvi. 580	1904
	McWhirter's shielded instruments	..	Elect. Eng., xxi. 330	1898
	Kelvin sector ammeter and voltmeter	M. Rypinski . .	Elect. Jour., iii. 588	1906
D	Hot-wire ammeter and voltmeter	J. Montpellier .	L'Élect., xxviii. 1	1904
E	An electrostatic voltmeter for very high pressures	G. Benischke . .	Elek. Zeit., xxii. 265	1901
	On the use of capacities as multipliers in connection with electrostatic voltmeters on alternate current circuits	E. W. Marchant . G. W. Worrall .	Elect., li. 1000 .	1903
	Electrostatic voltmeter .	S. M. Kintner .	Elect., lv. 705 .	1905
	Leakage Indicators.			
	A leakage indicator . .	..	Elect., lv. 911 .	1905
	Leakage indicators . .	F. C. Raphael .	Elect., lv. 348 .	1905
	Ground detectors and their connections	J. T. Coe . . .	Am. Elect., xvii. 634	1905
B_2	A three-phase leakage indicator	..	Elect., lvi. 802 .	1906
	Leakage indicators . .	A. F. Harris . .	Elect. Mag., vii. 150	1907
E	Electrostatic ground detectors	..	Elect. Wld., xxxvii. 743	1901
	Insulation measurement by means of electrostatic voltmeters	J. Sahulka . .	Elek. Zeit., xxv. 547	1904
	Wattmeters.			
B_1	Siemens and Halske wattmeters	A. Raps . . .	Elek. Zeit., xx. 665	1899
	Theory and use of the alternate current wattmeter	C. V. Drysdale .	Elect., xlvi. 774 .	1901
	Wattmeter and phase indicator	..	Elect. Wld., xxxvii. 838	1901

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LIST OF REFERENCES—*continued.*

—	Name of Paper.	Author.	Where to be Found.	Date.
	Use of iron in alternate current instruments	W. E. Sumpner .	Proc. I.E.E., xxxiv. 144	1904
	Iron-cored wattmeter .	C. Olivetti . .	Elect., liv. 1050 .	1904
	Ditto	C. V. Drysdale .	Elect., lv. 472 .	1905
	Determination of wattmeter correction factor	S. P. Smith . . C. V. Drysdale . K. Edgcumbe . H. W. Wilson .	Elect., lv. 344, 389, 430, 477, 516, 557, 574, 602, 676	1905
	Recording wattmeters .	J. Willis . . . L. Imlay . . .	Elect. Wld., xlix. 334	1907
D	Combined ampere-volt-wattmeter	M. B. Field . .	Elect. Rev., xliii. 767, 811	1898
E	Electrostatic wattmeter .	J. Swinburne . .	Elect., xxvi. 571 .	1891
	Ditto	G. L. Addenbrooke	Elect., li. 811, 845	1903
	Phasemeters.			
B_1	An Instrument for determination of phase difference with alternate currents	M. Dolivo-Dobrowlsky	Elect., xxxiii. 610	1894
	Power-factor indicator .	A. J. Bowie . .	Elect. Wld., xxxvi. 644	1900
	Phase indicator . . .	..	Elect. Wld., xxxvii. 838	1901
	Power-factor indicators .	W. H. Browne .	Proc. A.I.E.E., xviii. 287	1901
	Direct reading power-factor indicator	.. ..	Elect., li. 168, 300, 339, 381.	1903
	Use of iron in alternate current instruments	W. E. Sumpner .	Proc. I.E.E., xxxiv. 144	1904
	Power-factor meters and their application	P. MacGahan .	Elec. Jour. i. 462.	1904
	The power-factor indicator	H. W. Richardson	Elect. Wld., xliv. 1089	1904
	Theory of phasemeters .	W. E. Sumpner .	Phil. Mag., xi. 81	1906
	Phasemeters and their calibration	W. E. Sumpner .	Elect., lvi. 760 .	1906
	Frequency Indicators.			
B_1	Frequency indicator . .	P. Lincoln . .	Proc. A.I.E.E., xviii. 262	1901
B_1	G.E.C. frequency meter.	..	Elect. Wld., xxxvii. 688	1901
F	Speed indicators . . .	C. Feldmann . .	Elect. Wld., xliv. 860	1904
F	Resonance instruments .	Dr. Hartmann-Kempf	Elek. Zeit., xxv. 44	1904

Digitized by Google

LIST OF REFERENCES—*continued.*

Name of Paper.	Author.	Where to be Found.	Date.
A new type of frequency indicator	A. S. Langsdorf .	Elect. Wld., xlvi. 1029	1905
Frequency meters . .	F. Conrad . .	Elect. Jour. iii. 535	1906
Magnets.			
On the induction coefficient of hard steel magnets	B. O. Peirce . .	Am. Jour. Sc., ii. 347	1896
On temperature coefficient of certain seasoned hard steel magnets	A. Durward . .	Am. Jour. Sc., v. 245	1898
Magnetic properties of tempered steel	Mme. Curie . .	Elec. Rev., xliv. 40, 75, 112	1899
Phase-Splitting Devices.			
Siemens and Halske . .	..	Sc. Abs., No. 435	1898
Compensating devices .	C. H. Gerhardi .	'Electricity Meters,' Book, p. 13	1906
Recording Instruments.			
Curve drawing or graphic recording instruments	H. Young . . .	Am. Elect., xvi. 283	1904
Inkless recorders . . .	..	Elect. Rev., lvii. 481	1905
Graphic recording instruments	P. MacGahan .	Elect. Jour., iii. 297	1906
Recording wattmeters .	J. Willis . . . / L. Imlay . . .	Elect. Wld., xlix. 334	1907
Transformers.			
Measuring instrument transformers	F. Punga . . .	Elect., li. 1009 .	1903
Operation of the series transformer	E. L. Wilder . .	Elect. Jour., i. 451	1904
Current transformers for instruments	W. P. F. . . .	Elect. Rev. lix. 563	1906
Phase displacements in resistance and transformers	C. V. Drysdale .	Elect., lviii. 160 .	1906
The current transformer .	K. L. Curtis . .	Proc. A.I.E.E., xxv. 715	1906
Series transformers for wattmeters	L. W. Wild . .	Elect., lvi. 705 .	1906

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LIST OF REFERENCES—*continued.*

–	Name of Paper.	Author.	Where to be Found.	Date.
	Miscellaneous References.			
	Electro-dynamic rotation by means of alternate currents	G. Ferraris . .	Elect., xxi. 86 .	1888
	Electro-dynamic repulsion	J. A. Fleming .	Elect., xxvi. 567, 601	1891
	Measurement of fault resistance	S. A. Russell . .	Elect. Rev., xlii. 251	1898
	Electrical alloys . . .	R. Appleyard. .	Elect. Rev., xlii. 536, 607	1898
	Magnetic fluxes in meters and other instruments	A. Campbell . .	Phil. Mag. S. 5, xlvii. 1	1899
	Accurate measurement of alternating and multiphase currents	G. L. Addenbrooke	Elect., xlv. 901 .	1900
	Effect of wave-form on solenoid and induction instruments	G. Benischke . .	Elek. Zeit., xxii. 301	1901
	Use of condensers with alternate current measurements	W. Peukert . .	Elek. Zeit., xxv. 231	1904
	Methods of measurement of high electrical pressure	S. M. Kintner .	Elect., lv. 702 .	1905
	Shunt resistance and temperature compensation for ammeters	A. Campbell . .	Proc. I.E.E., xxxv. 197	1905
	Reading error of indicating instruments	B. Brackett . .	Elec. Jour., ii. 704	1905
	Accurate speed, frequency and acceleration measurement	C. V. Drysdale .	Elec. Rev., lix. 363	1906

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GREAT WINDMILL STREET, W., AND DUKE STREET, STAMFORD STREET, S.E.

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